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NUMERICAL MODELLING OF SHALLOW FOUNDATION ON EXPANSIVE SOIL UNDER WET AND DRY CYCLES

Muhammad Rehan Hakro^{1*}, Mohammad Ahsan Channa², Imtiaz Ali Hakro³

Abstract

The research paper investigates the behaviour of shallow foundations on expansive shale soil under varying hydrological conditions, such as rainfall and drought. Expansive soil experiences volumetric changes due to fluctuating water conditions, resulting in differential movements of foundations. Previous studies on user-defined swelling rock models have predominantly addressed tunnel behaviour. This study extends the application of such models to simulate more realistic field conditions, focusing on the deformation and load-bearing response of shallow foundations subjected to swelling pressures under varying geotechnical and environmental conditions. The new use of the User Defined Swelling Rock Model in Plaxis 2D FEM software allowed settlement and swelling to be simulated under realistic conditions, such as varying soil saturations, stages of loading, dry-wet cycles, and time-dependent evolution of swelling. Settlement and swelling computations were simulated using Plaxis 2D FEM software under different soil saturation, loading, and rainfall conditions. The first part of the study was to determine the swelling characteristics of expansive soil of study area of Jamshoro and model parameters such as cohesion, angle of internal friction, swelling pressure, swelling potential and modulus of elasticity. Laboratory testing and calibration was also performed to determine the model parameters. After this numerical modelling was performed with swelling rock model to observe the heaving of shallow foundation due to swelling of expansive soil in wet conditions. Modelling in Plaxis 2D conducted model studies with a 100 kPa foundation pressure on shale soil, followed by unloading and saturation. Short-term heaving remained within tolerable limits. However, over 100 days, extensive vertical movement exceeding the tolerable limit was observed due to continuous shale swelling. Rapid water table increase caused significant vertical movement, but gradual rise reduced it. The depth of the shale layer, underlain by stiff limestone, significantly influenced foundation movement, even at 1 meter depth causing intolerable movements.

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Expansive Soil, Shallow Foundation, Wet and Dry conditions, Shale

1.0 INTRODUCTION

Expansive soils, also known as swelling soils, pose significant challenges to the construction industry worldwide. These unique types of soils exhibit substantial volume changes in response to variations in moisture content, causing detrimental effects on infrastructure, especially shallow foundations. Shallow foundations transmit the entire structure's load to the soil at a relatively shallow depth. The design of shallow foundations primarily revolves around considerations of settlement, heaving, and bearing capacity. In many instances, settlement takes precedence over bearing capacity when designing shallow footings. Nevertheless, in certain situations, expansive-related heaving and settlement caused by shrinkage may also be significant factors to consider. Buildings erected on expansive soil may experience significant deformation or pressure due to soil swelling, leading to potential harm to their structural integrity (Elarabi, 2012). In Pakistan, expansive soils are widespread and have led to significant structural damage in various regions, including cracks in single- and double-story buildings and the uplift of floor slabs (Farooq, 1996) (Akbar & Farooq, 2002). To mitigate these issues and reduce repair expenses, engineering designs must consider and address the impacts

of soil swelling (Lim & Siemens, 2016). The unpredictability of their behaviour makes it imperative to comprehensively study and understand their interactions with foundation systems. A suggested explanation for soil swelling involves the interlayer expansion of the clay mineral Montmorillonite. The unique molecular structure of Montmorillonite attracts and retains water molecules between its clay crystal sheets. When potentially expansive soils become saturated, Montmorillonite can absorb significant quantities of water into the gaps between its clay sheets. This absorption causes the sheets to separate further, resulting in an increase in soil pressure or expansion of soil volume. Conversely, soil swelling can also be attributed to intraparticle swelling resulting from the alignment of water films around clays with a high charge density (Keskin, Salimi, Ateyşen, Kahraman, & Vakili, 2023). Clay particles are predominantly flat and carry an electrical charge, often negative. This significant charge concentration on the surface of the clay particles causes bipolar water molecules to be attracted to them.

Expansive soils are predominantly composed of clay minerals, such as montmorillonite and illite, which have the

propensity to adsorb water molecules and expand, and desorb water, leading to shrinkage. This characteristic behaviour results in severe damage to shallow foundations, including uneven settlements, cracking, and heave, which can compromise the structural integrity of buildings and other structures (Hakro, Kumar, Ali, *et al.*, 2022; Hakro, Kumar, Almani, Ali, Hakro, Machaček, Nitsch *et al.* 2024). Clay swelling is a widespread occurrence found in soils and sedimentary rocks, and it can cause harmful stresses when the soil undergoes wetting or drying cycles. It is crucial to recognise the factors that influence this swelling to gain insights into the process and effectively prevent potential damage (Wangler & Scherer, 2008, Wang, Xu *et al.* 2024).

Over the recent past, numerous constitutive models have been designed to characterise soil behaviour. These models draw upon concepts from plasticity, elasto-plasticity, and non-linear elasticity theory. The significance of soil models has grown substantially alongside the advancement and application of computer-based techniques like finite element and finite difference methods. These computational methods typically involve several material constants and require sophisticated laboratory tests conducted under various stress paths. Stress path testing, whether performed in the laboratory or in the field, plays a vital role in formulating the constitutive laws governing soil materials. When subjected to axial and lateral loads, different elements within the soil experience distinct paths of loading or stress. Hence, determining the parameters of the constitutive model or calibrating the model constants becomes a crucial step in modelling geotechnical problems. These parameters are derived from the observed behaviour of the soil during laboratory or field tests. The continuum approach forms the basis for the finite difference method (FDM), finite element method (FEM), and boundary element method (BEM). Among these, the FEM comprises eight fundamental steps. These steps include discretisation, selecting a displacement model, defining strain-displacement and stress-strain relationships, deriving element equations, assembling and applying boundary conditions, solving primary unknowns, computing secondary unknowns, and interpreting the results. The FEM is versatile and can handle problems with material and geometric nonlinearities, complex boundary conditions, and non-homogeneities. It involves dividing the entire region of interest into discrete elements for analysis (Hemeda, 2019, 2022).

Numerous studies have been carried out on the settlement of shallow and deep foundations using various geotechnical software, such as Plaxis 2D, Plaxis 3D, GeoStudio, and others (Agraine, Bouali, & Messameh, 2020; Anand, Acharyya, & Dey; Anaokar & Mhaiskar, 2019; Byrne *et al.*, 2004; Chatra, Dodagoudar, & Maji, 2017; Dashti & Bray, 2013; Deb & Pal, 2021; Dias & Gripton, 2017; Enkhtur, Nguyen, Kim, & Kim, 2013). However, there is a limited body of research focusing specifically on foundations under expansive soil conditions. The numerical modelling of (Al-Busoda & Abbas, 2018) study examines pipelines supported on expansive soils, which are susceptible to uplift forces caused by soil swelling, leading to deformations and bending. The researchers utilized PLAXIS 3D-2013 software, employing the Hardening Soil Model for numerical modelling. They investigated different spacing

configurations of helical piles to mitigate the vertical movement of pipelines resting on expansive soil. The study of (Al-Busoda & Abbas, 2017) employed numerical modelling using PLAXIS 3D-2013 software with a hardening soil model to analyse towers situated on expansive soils. Such towers experience uplift and lateral forces resulting from soil swelling and wind loads. The swelling in expansive soil further induces lateral pressure on the tower foundation, leading to deformations and bending. To mitigate the vertical and lateral movement of towers built on expansive soil, various configurations of helical piles were considered. The issue with the preceding numerical analyses conducted on various structures situated in expansive soil lies in their utilization of conventional geotechnical models like Mohr-Coulomb and hardening soil model, employing volumetric strain to represent soil swelling. Nevertheless, in practical scenarios, the swelling phenomenon is intricately linked to the water level within the soil medium. The other numerical modelling study was conducted by (El-Shamy, El-Mossallamy, Abdel-Rahman, & Ali, 2019) to calibrate the swelling rock model in Plaxis with Oedometer test.

The conducted oedometer swell tests on the same soil using two techniques: the different pressure method and the huder-amberg method. They compared the results and procedures of both methods, identifying the strengths and limitations of each. As a result of this comparison, the huder-amberg method was selected for all subsequent tests due to its superior performance in determining swelling parameters. To ensure accurate and comprehensive results for the swelling parameters, they applied Grob's 1d swelling law to the experimental data. Furthermore, they developed a new user-defined swelling constitutive model in the finite element software Plaxis to simulate swelling soil behaviour numerically. The model's suitability was verified through numerical simulations based on one of the huder-amberg oedometer tests using Plaxis software's oedometer soil test facility.

Expansive ground is identified by evaluating factors such as moisture levels, swell potential, Atterberg Limits, and suction capacity of the expansive material (Fityus, Smith, Allman, & Engineering, 2004, Johnson & Snethen, 1978, Mofiz & Islam, 2010). The assessment of uplift movements in expansive soil/rock is a highly intricate hydro-mechanical problem (Marino *et al.*, 2017). The swelling and consolidation settlements within shale formations result in structural issues, such as the development of cracks and significant settlement in buildings. In Jamshoro numerous structures constructed on shallow foundations situated on expansive shale soil, leading to extensive cracks and settlement due to the uplift of these shallow foundations. Unfortunately, no study has been conducted at the Jamshoro site, where the majority of the shallow soil layers consist of expansive shale. In this study the numerical modelling using PLAXIS 2D will be employed to investigate the behaviour of shallow foundations built on expansive shale layers. The modelling will incorporate a user-defined Swelling Rock Constitutive Model, specially designed for this analysis. This study comprises of field investigation, laboratory testing, validation of model with small scale physical model and numerical simulations of shallow foundation under different cycles of dry-wet and wet-dry condition. This study

will be helpful the geotechnical engineer to better design the shallow foundation under expansive soil considering wet and dry cycles.

2.0 RESEARCH METHODOLOGY

In this study the numerical modelling was performed with FEM geotechnical software Plaxis 2D to assess the heaving and settlement of foundation under different loading and wet and dry cycles. Initially the laboratory testing was performed to determine the model parameters. The swelling rock model was used for simulating the settlement and swelling response of expansive soil under dry and wet conditions. The constitutive model for swelling rock relies on the time-dependent swelling behaviour of the rock. Initially developed by Professor Thomas Benz of NTNU, the model was later enhanced by Bert Schädlich of Tugraz for PLAXIS 2D. This swelling rock model draws from the research of Anagnostou (1993) and Heidkamp & Katz (2002), encompassing stress and time-dependent aspects of swelling deformation.

The provided paper utilized a finite element numerical simulation through Plaxis software, a two-dimensional analysis tool designed for assessing stability, deformation, subsidence, compaction, and leakage under both static and dynamic scenarios within the geotechnical field (Tsegaye, 2010). To ensure an accurate representation of the factors influencing the mass, this research work incorporated numerous parameters relevant to soil swelling susceptibility analysis into the model. Consequently, the model's development and execution encompassed four key phases: establishing the geometric mass configuration, defining boundary conditions, allocating material properties and behavioural models, and conducting mechanical analysis considering saturated shale conditions. The model parameters were 100 x 10 meters in model dimensions have been so selected that the deformation in the soil does not intersect the model's boundaries.

The geotechnical parameters of soil and model parameters are mentioned in Table 1. The working conditions of Plaxis 2D software are described as follows. Plaxis 2D: The finite element analysis was conducted using Plaxis 2D version 21.2. The primary objective of the study was to numerically replicate the soil behaviour of the Jamshoro Shale sample under conditions of plain strain. This was achieved by implementing the elastoplastic Mohr-Coulomb model and a specialized swelling rock model. The analysis was specifically designed to represent drained state conditions. The foundational structure's base was modelled using a standard linear elastic material. Lateral constraints were applied along the axis of symmetry, and appropriate vertical boundaries were imposed, while the bottom boundary was confined both horizontally and vertically to mimic real-world conditions more accurately.

Notably, both the rock and soil exhibited highly nonlinear behaviour when subjected to loading conditions. The line loads on the footing were derived from distributed loads, and the phased construction technique allowed for sequential activation of the footing after applying the line load. The model geometry was effectively partitioned into components to generate a mesh, with a medium-sized mesh chosen to strike a balance between precision and computational efficiency. Thorough

consideration of the model proportions ensured that direct contact between ground deformation and model boundaries was avoided. The soil model was characterized by dimensions of 20 meters in width and 10 meters in depth. To ensure successful simulations, the initial stresses were specified using either the "K0-procedure" or "Gravity loading" options, with the K0 approach being the recommended choice for horizontal surfaces. Incorporating the "standard fixity" criterion, the numerical model constrained the bottom edge to prevent vertical and horizontal movement, while the vertical edges were subjected to horizontal fixity, preserving the unchanged condition of the bottom edge.

Table 1: Model parameters
(UDSM - Swelling Rock Model Manual)

Symbol	Unit	Values
c^*	kN/m ²	22
ψ	°	0
σ_{tens}	kN/m ²	0.001 (assumed)
E_i	kN/m ²	24711
E_p	kN/m ²	24711
v_{pt}	--	0.3
v_{tz}	--	0.3
G_{pt}	kN/m ²
A_0	1/day	0.033
A_{el}	1/day	---
A_{pl}	1/day	-
K_{qp}	--	10%
K_{qt}	--	10%
σ_{qop}	kN/m ²	100
σ_{qot}	kN/m ²	100
Swell_ID	--	3
Water	--	1

3.0 RESULTS AND DISCUSSION

From the laboratory investigation it was observed that the Jamshoro soil consist of shale having higher values of Atterberg's limits i.e., liquid limit of 80 % and plastic limit of 35 % and PI as 45. According to AASHTO and Unified Soil Classification System (USCS) the soil classified as A-7-5 and CH respectively. The free swell index (FSI) was 120 % and swelling pressure was 100 kPa. According to the laboratory test results, which include liquid limit, plastic limit, Free Swelling, and Swelling Pressure tests on the soil, it has been observed that the structure's shallow foundation is prone to significant expansion-related heaving, settlement caused by shrinkage, and consolidation settlements under varying structural pressures. The sieve analysis of soil is given in Figure 1. The result of sieve analysis align with Atterberg's and indicating the soil as clayey soil with large swelling potential.

The User Defined Soil Model (UDSM) Swelling Rock Model was used in Plaxis 2D to specifically capture the swelling strains due to hydration, which cannot be reproduced

accurately by conventional soil models. It was successfully used in past research to model swelling pressure, heave, and stress redistribution (Al-Maamori, El Naggar et al. 2018) and is therefore a good option for expansive soils and weak rocks. Calibration was performed in accordance with the Huder–Amberg Oedometer procedure, loading soil initially in dry conditions and later under saturated conditions to monitor swelling (Plaxis Manual, 2018). The Plaxis 2D deformation curve best simulated laboratory measurements, ensuring that the employed model is a fair representation for simulating the swelling characteristics of the tested soil as shown in Figure 2.

By following the outlined steps of the modelling process described in the previous section, the mechanical stages are sequentially implemented. The step model is then computed and executed to analyse the deformations, displacements, and stress-strain behaviour under the influence of expansive soil loading. To explore the fundamental behaviour of shallow foundations on shale layers during loading, unloading, and full

saturation, a series of models were created and examined. The study involved subjecting the foundation to a pressure of 100 kPa on the shale soil, followed by complete unloading to 0 kPa. Subsequently, the model was fully saturated to a degree of saturation of 100%, as illustrated in the Figure 3. The results of the model, as shown in Figure 3, indicate that the foundation settled, moving vertically downward by 15 mm at the centre of its centroid when subjected to a 100 kPa load. Upon unloading the foundation to zero pressure, it moved upward by 12 mm. After applying full saturation, the foundation experienced further upward movement or heaving of 8 mm, attributed to the expansion of the swelling shale. The concept that when expansive soils absorb water, they undergo volume expansion due to swelling mechanisms. This expansion generates internal stresses within the soil mass. It's important to understand that this is a simplified representation of the complex physical and chemical processes occurring at the microstructural level during soil swelling (Alonso, Vaunat, & Gens, 1999; Fredlund, Rahardjo, & Fredlund, 2013; Nelson & Miller, 1997).

The study investigated the behaviour of a foundation on shale soil subjected to different loading and saturation conditions. The foundation pressure was varied from 100 kPa to 20, 40, 60, and 80 kPa, and the degree of saturation was set to 100% at each loading condition. The results showed that under a foundation pressure of 100 kPa, the foundation settled by 15 mm at its centre. When the pressure was reduced to 20 kPa, the foundation moved upward by 11 mm. Upon full saturation, the foundation further heaved upward by 9 mm due to the expansion of the swelling shale.

Similarly, for foundation pressures of 40, 60, and 80 kPa, the settlement was 15 mm at the centre under the initial loading. As the pressure decreased, the foundation moved upward by 8 mm, 6 mm, and 4 mm, respectively. With full saturation, the foundation heaved upward by 9 mm in all cases. Regardless of the loading condition, when the foundation was fully saturated, it experienced upward movement (heaving) ranging from 8 to 10 mm. The initial settlement under a pressure of 100 kPa was 15 mm, which is within the acceptable limit of 25 mm for shallow foundations (Bowles 1996, (Terzaghi, Peck *et al.* 1996).

In the Figure 4, under a constant load of 100 kPa, the foundation experiences a settling of 8 mm in the absence of moisture within the shale soil. However, when the soil reaches full saturation for a prolonged period of 100 days, a substantial upward movement of the foundation by 87 mm takes place due to the swelling or heaving of the completely saturated shale soil. These findings underscore that despite the higher structural load of 100 kPa, a noteworthy vertical displacement of the foundation transpires over a reasonable 100-day span due to the swelling properties of the saturated shale. Moreover, the upward motion resulting from the expansion of the swelling shale is notably remarkable, measuring 170 mm and 150 mm for two and four-story structures respectively, when subjected to typical structural pressures of 25 kPa and 50 kPa. As moisture absorption causes expansive soil to swell, it imposes an upward pressure on the foundation, potentially leading to its elevation and thereby presenting risks to the structural soundness and overall stability of the building.

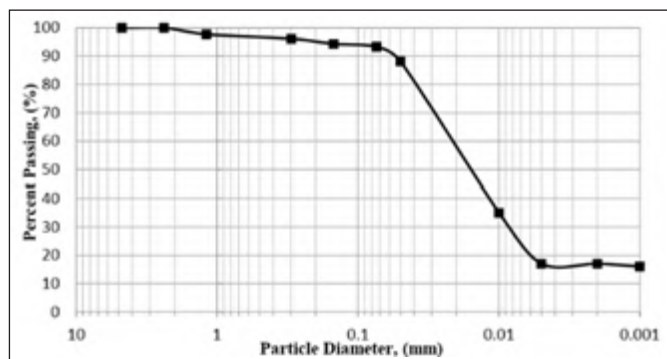


Figure 1: Sieve analysis curve

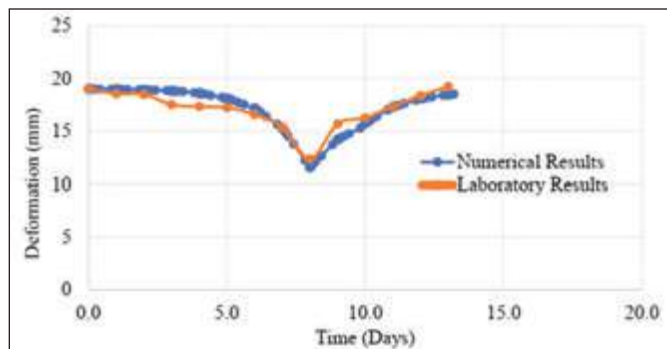


Figure 2: Calibration of swelling rock model

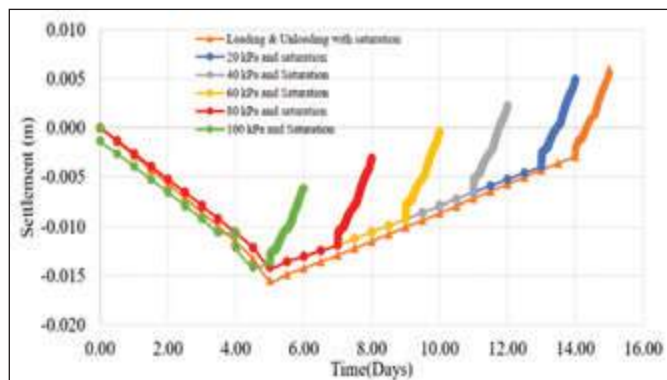


Figure 3: Loading-unloading and saturation of soil

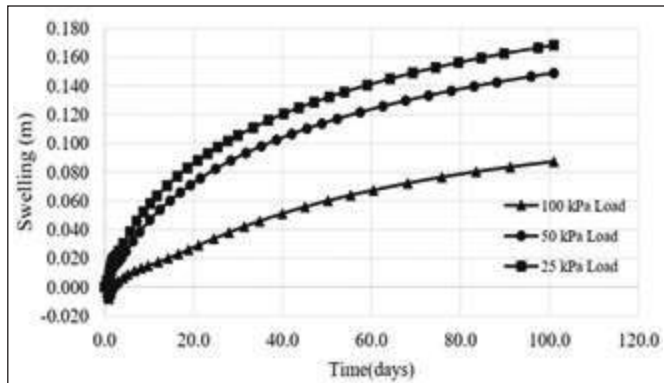


Figure 4: Behaviour of foundation at saturation under different loads

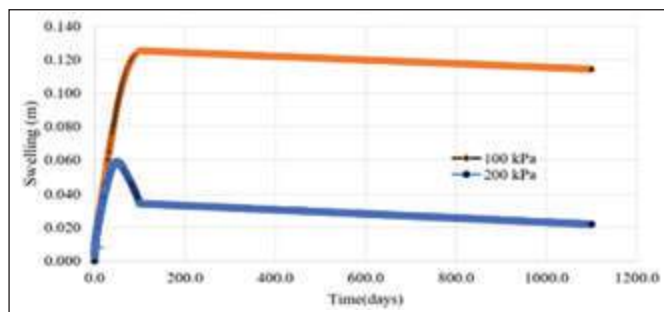


Figure 5: Saturated to dry conditions under 100 kPa and 200 kPa Load

These findings are in agreement with the research by (Khennouf and Baheddi, 2020), who indicated more than 130 mm heave at a 100 kPa load in their FLAC 3D simulations of shallow foundations on fully saturated expansive clay in N'Gaus, Algeria. Their results confirm that substantial uplift—anywhere from 130 mm to 148 mm—can happen even under moderate loads, thus validating swelling-induced foundation movement as proposed in this research.

This set of model simulations commenced by fully saturating the soil and subsequently subjecting it to a gradual drying process marked by increasing suction levels, all while maintaining constant pressures of 100 kPa and 200 kPa. The outcomes, visually portrayed in Figure 5, provide compelling insights. At a structural pressure of 100 kPa, a load equivalent to the standard magnitude experienced by a 10-story building, the foundational structure displays minimal, practically negligible, movement. This observation underscores the resilience of the foundation under this common structural load.

However, the dynamics change notably when the load is intensified to 200 kPa, effectively doubling the pressure. Under this escalated pressure scenario, a substantial settlement of 30 mm ensues. This settlement is primarily attributed to the process of shale shrinkage triggered by the elevated pressure. Remarkably, this substantial settlement phenomenon perseveres over an extended period, exhibiting a consistent behaviour in the long term. In essence, this series of models rigorously demonstrates the interplay between soil saturation, pressure levels, and resultant settlement. The findings emphasise that while the foundation maintains stability under typical loads, doubling the pressure can lead to substantial and persistent settlement due to the characteristic shrinkage

of shale. These insights contribute to a more comprehensive understanding of the foundation's behaviour under varying conditions and serve as a valuable reference for construction and geotechnical considerations.

From these findings, it can be concluded that there is no substantial settlement of the footing at a structural pressure of 100 kPa when the soil transitions from its initial saturated state to a dry state, representing the load of a 10-story building foundation. However, if the soil becomes dry from its initial saturated conditions under a very high structural pressure of 200 kPa, representing the load of 20-story buildings, there may be significant settlement of the foundation. When the water table of the ground is raised abruptly to ground level, while maintaining a constant bearing pressure of 100 kPa over a period of 100 days, there is a significant upward movement of the foundation, reaching 75 mm. This movement is attributed to the heaving or swelling of the shale soil at full saturation. On the other hand, when the water table is gradually increased to ground level in multiple steps, while keeping the load constant for the same period of 100 days, the foundation experiences an upward movement of 25 mm due to the heaving or swelling of the shale soil.

These results demonstrate that there is substantial vertical movement of the foundation during a reasonable 100-day timeframe caused by the heaving or expansion of the swelling shale under a high structural load of 100 kPa when the water table is raised abruptly. However, this movement reduces to tolerable limits of 25 mm when the water table is elevated in multiple steps. Numerous studies primarily focused on the larger mechanical characteristics and smaller underlying mechanisms of expansive soil. Commonly, tests involving cycles of wetting and drying were conducted (Gallage & Uchimura, 2016; Tang *et al.*, 2020). The outcomes indicated a strong correlation between the larger mechanical traits and the soil's capacity to absorb and release water. Of particular significance was the decline in cohesion, internal friction angle, and shear strength of expansive soil as the number of wet-dry cycles increased (Wang, Tang, Cui, Shi, & Li, 2016). The intricate microstructure of expansive soil was responsible for both its characteristics of swelling and shrinking, as well as the weakening of its ability to hold moisture. Similar to other types of clay, the expansion and contraction process can be dissected into macro- and micro-structural components. The expansion mechanism, triggered by water absorption, centred on the creation and thickening of water films (Manca, Ferrari, & Laloui, 2016). This generated a "wedge" force among clay particles, leading to increased particle spacing and expanded pores. As a result, the ultimate strength of expansive soil is governed by the arrangement of pores within the soil.

This series of model simulations encompassed a diverse range of shallow foundation sizes, spanning from isolated footings to more extensive raft foundations. The impact of varying footing dimensions on the behavior of swelling shale under a bearing pressure of 100 kPa is depicted in Figure 6. For instance, an isolated footing measuring 2 meters, typically suited for 2-story residences, exhibited a vertical displacement of 100 mm. However, when the footing dimensions were

enlarged to 4 meters, typically employed for 4-story buildings, the vertical displacement decreased to 87 mm. Similarly, when utilising a larger 8-meter footing, often employed for raft or mat foundations, the vertical movement showed a notable reduction. Subsequently, as the footing dimensions expanded further to 16 meters, the vertical movement diminished even more significantly to 22 mm.

These results highlight a clear trend: as the size of the foundation increases, the vertical movement of the footing diminishes. Eventually, this reduction reaches levels deemed tolerable for building structures. Consequently, the findings propose that opting for relatively larger isolated footings or raft foundations could offer benefits in curbing footing movements to acceptable thresholds for the overall structure's stability.

Figures 7 & 8 provide insight into the impact of altering the depth of the overlying shale layer, situated above a rigid limestone rock layer, on the foundation's movement. The simulation process encompassed two phases: initially observing settlement under dry conditions, followed by elevating

the water level near the base of the foundation to observe swelling. The recorded values for swelling were as follows: 76 mm, 71 mm, 68 mm, 59 mm, 51 mm, 43 mm, and 41 mm for shale depths of 10 meters, 7 meters, 6 meters, 5 meters, 4 meters, 3 meters, 2 meters, and 1 meter, correspondingly. This analysis underscored a clear trend: as the depth of the shale layer decreased, the foundation's movement also exhibited a reduction, eventually reaching minimal values.

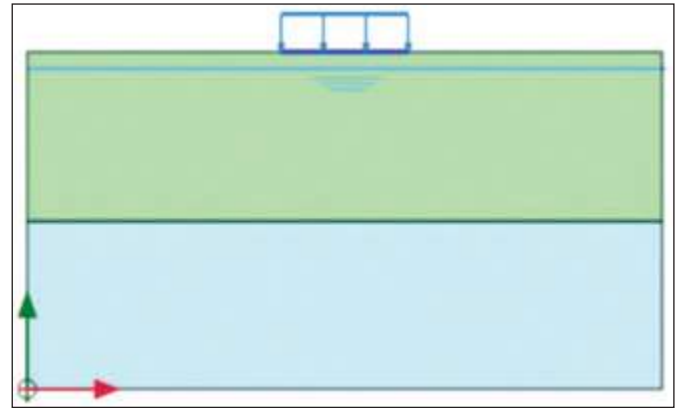


Figure 9: Shale layer below limestone

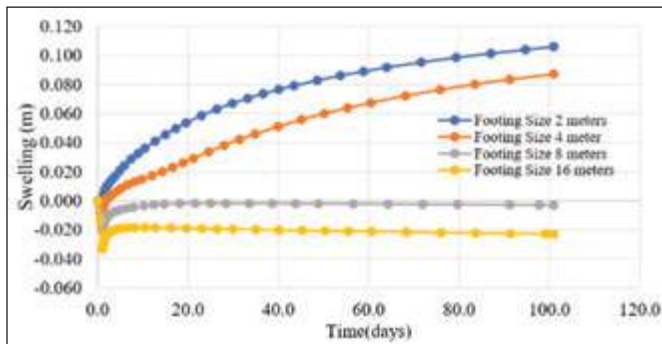


Figure 6: Footing size and heaving of footing

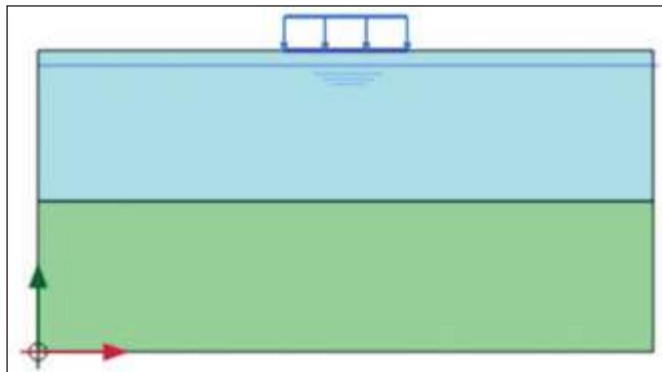


Figure 7: Effect of limestone below shale layer

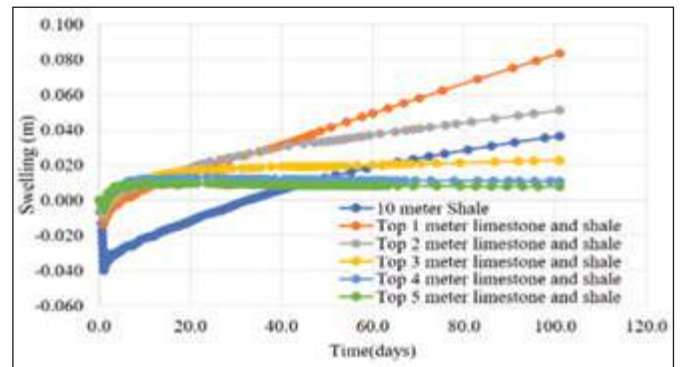


Figure 10: Swelling of shale below limestone

Figures 9 and 10 further delve into the influence of the depth of the limestone rock layer beneath the shale on the foundation's movement. The simulations followed a similar pattern, observing settlement under dry conditions and subsequently triggering swelling by raising the water level near the foundation's base. The vertical upward movement of the foundation displayed distinct variations. For instance, a 1-meter top layer of limestone rock resulted in a substantial 93 mm of vertical heaving movement, while a 2-meter limestone layer yielded 51 mm of movement. With the shale layer extending to its full depth, the movement decreased to 36 mm.

Notably, as the depth of the limestone layer increased, the swelling effect diminished, reaching a mere 7 mm with a 5-meter limestone layer. Interestingly, for limestone layers measuring 1 to 2 meters, the footing movement resembled that of a full-depth shale layer. Nevertheless, with thicker and more rigid limestone layers, the swelling potential of the soil diminished, leading to a significant reduction in the vertical foundation movement. The collective findings of this study culminate in a compelling conclusion: the strategic incorporation of an appropriate thickness of surface limestone layer can effectively mitigate the vertical movement caused by swelling. Such a

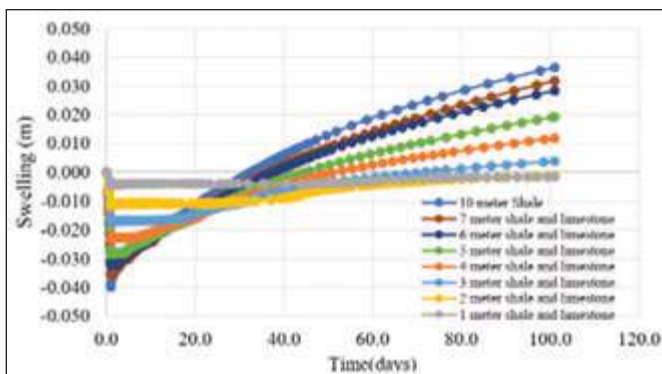


Figure 8: Effect of limestone below shale layer on swelling

layer can substantially diminish the movement to an almost negligible extent. This understanding offers valuable insights for construction practices aimed at minimising the detrimental effects of swelling on foundation stability.

4.0 CONCLUSION

The core aim of this research study was to comprehensively investigate how shallow foundations, situated on expansive soil, respond when exposed to a range of wet and dry cycles. This inquiry was conducted through the application of the Finite Element Method (FEM) Plaxis 2D software. The research unfolded in three main phases: i) Investigation and testing in both laboratory and field settings, and ii) Numerical Modelling using Plaxis 2D. The initial phase revolved around characterising the expansive soil profiles present at the research site. This involved extracting soil samples via rotary drilling and subsequently determining relevant soil parameters through laboratory examinations. The precision of these parameters was ensured via calibration. The second phase delved into numerical modelling, employing Plaxis 2D in tandem with the Swelling rock soil model, which facilitated a comprehensive analysis of foundation behaviour across diverse soil conditions.

4.1 Key Insights

- Subsurface analysis revealed cohesive deposits with considerable potential for volume change. The soil composition encompassed assorted expansive layers at varying depths, categorised as A-7-5 and CH according to the AASHTO and USCS classification systems respectively.
- Weathered and fissured limestone, along with shale layers, were identified at different depths within the research area.
- The soil in question was identified as swelling shale, characterised by a significant plasticity index and notable activity. This was predominantly attributed to the presence of active clay minerals such as Montmorillonite. The expansive nature of the soil manifested through pronounced swelling pressure and substantial potential for expansion.
- A subsequent series of model studies targeted the transient behaviour of shallow foundations situated on shale layers, considering conditions involving loading, unloading, and complete saturation. These models exposed the shale soil to a foundation pressure of 100 kPa, followed by a complete reduction to 0 kPa, and eventual full saturation.
- Results revealed that the short-term upward movement or heaving of the foundation remained within allowable thresholds of 25 mm for structures, regardless of the loading conditions.
- However, over a span of 100 days, noteworthy vertical foundation movement exceeding the permissible 25 mm limit for structures was observed. This movement endured even when the structural pressure varied between low (25 kPa) and high (100 kPa) bearing pressures. The persistence of this substantial vertical movement was attributed to the prolonged swelling of the shale, even during near-consolidated states under foundation loads or during unloading.
- Additionally, within a reasonable timeframe of 100 days, significant vertical foundation movement occurred due to

the expansion of the swelling shale, particularly when the water table experienced rapid elevation. However, this movement subsided to permissible levels when the water table was gradually raised.

- These observations underscore the critical necessity of factoring in both short-term and long-term consequences of shallow foundations resting on swelling shale. Managing fluctuations in the water table emerges as a pivotal determinant in curbing vertical foundation movement, thus safeguarding structural stability and integrity.
- In conclusion, this study serves to advance the comprehension of how shallow foundations respond when placed on swelling shale, emphasising the importance of meticulous evaluation encompassing diverse conditions. This comprehensive assessment guides the development of effective strategies to mitigate potential risks and optimise structural performance.

4.2 Limitations of Work

The current study is based on the numerical modelling of shallow foundation of expansive soil of Jamshoro, therefore conclusions cannot be applied to other geographical locations or other expansive soils. ■

AUTHORS' CONTRIBUTIONS

Muhammad Rehan Hakro	Conceptualisation, study design, Writing review, editing, Data collection, methodology, and formal analysis.
Mohammad Ahsan Channa	Data validation, visualisation, and software software implementation.
Imtiaz Ali Hakro	Literature review, supervision, software implementation.

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PROFILES



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EVALUATION OF THE FACTORS AFFECTING RESIDENTIAL BUILDING MAINTENANCE FOR PROGRAM PERUMAHAN RAKYAT (PPR): USER'S PERSPECTIVE

Kai Wen Khor

Abstract

Program Perumahan Rakyat (PPR), also known as The People's Housing Program, is an affordable housing programmes in Malaysia for the government to address the issue of squatters living illegally in urban areas. However, the building of PPR have degraded and grown increasingly vandalised, the issue of building maintenance is a major concern and still on the rise. The residents of PPR have been negatively impacted by this persistent and poorly handled maintenance issue. Hence, the purpose of this study is to enhance the building maintenance of PPR, ultimately fostering a harmonious living environment for its occupants. A total of 380 respondents who are residents live in PPR, Kuala Lumpur was received. The data had been analysed by Statistical Package for Social Science (SPSS) and tabulated using the Cronbach's Alpha Reliability test, and measure of central tendency. In the Cronbach's Alpha Reliability test, all data had successfully exceeded the value of 0.900, which indicates the data are highly reliable to be used for analysis. The findings revealed that inappropriate material selection is the primary factor affecting building maintenance. The study also emphasises the importance of providing regular training in construction industry. This research is intended to be valuable to the Malaysian construction stakeholders in delivering the factors affecting residential building maintenance, Post Occupancy Evaluation (POE) from the perspectives of the users, and the strategies in improving the building maintenance.

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Program Perumahan Rakyat (PPR), People housing program, Post occupancy evaluation, Building maintenance

1.0 INTRODUCTION

One of the most significant affordable housing programmes in Malaysia is known as Program Perumahan Rakyat (PPR). The main purpose for the Malaysian government in constructing it is to offer low-income people access to affordable housing and to address the problem of squatters living illegally in urban areas (Hashim, *et al.*, 2015). However, PPR provided by the government faced problems in maintenance and service. Even though the government allocates a budget for PPR within the first 5 years, however, once the period has passed, the maintenance cost for the PPR will be reduced or eliminated (Sulaiman, Hasan, and Jamaluddin, 2016).

Building maintenance expenditures are significant all over the world, representing almost 50% of the overall construction sector revenue (Lateef, 2009). Tan, *et al.*, (2014) specified that the maintenance cost in the US market is foreseen to grow by 5.60% per year. The maintenance cost involves over two-thirds of contracts and signifies nearly 50% of the construction firm's overall revenue in many countries such as Hong Kong, the USA, and Saudi Arabia. (Islam, *et al.*, 2021). According to Kwon, *et al.* (2020), in a large-scale building, the maintenance-related cost for mechanical, electrical, and plumbing (MEP) makes up about 50% of life cycle cost (LCC).

The main functional criteria of a building are interior comfort, weather tightness, optimal use, durability, strength, and stability. Consequently, authorities, experts, and professional bodies who are considered to have an appropriate understanding of the needs and expectations of the inhabitant plan, build,

develop, and manage buildings following the specifications and standards (Awasho and Alemu, 2023). Post Occupancy Evaluation (POE) is a continuous process that systematically assesses the performance and efficiency of one or more building-related components concerning a range of factors, such as sustainability, aesthetics, accessibility, productivity, cost-effectiveness, functionality, safety, and security (Zimring, *et al.*, 2007). POE offers immense possibilities for enhancing the performance of a building when occupants are used as a benchmark in evaluation, covering technical performance and satisfaction of the occupants (Mustafa, 2017). Therefore, Post Occupancy Evaluation (POE) will be in use as a tool to evaluate the satisfaction of the occupants, and as a guide for future development in helping to improve the design and performance of a building (Nurhayati, *et al.*, 2015).

Based on the Malaysian Budget 2016, the Ministry of Urban Wellbeing, Housing, and Local Government (KPKT) will receive an allocation of RM863 million to continue PPR's plan to develop 22,300 apartments and 9,800 terrace homes. In Malaysia, there are a vast number of buildings, and the number is growing in the public and private sectors. (Lateef, 2009). Nevertheless, Malaysia continues to have a problem with poor building maintenance practices, and neither the public nor the private sectors can successfully maintain their structures due to a variety of problems (Hauashdh, *et al.*, 2020). Hence, the objectives of this research are to identify the factors that affect building maintenance, to evaluate factors affect building

maintenance by using Post Occupancy Evaluation (POE), and to determine the strategies in improving building maintenance.

2.0 LITERATURE REVIEW

In this study, several papers and journals which are related to the factors affecting building maintenance for PPR from the point of view of the user's perspective will be discussed. Next, the POE technique will be used and discussed the factors affecting building maintenance. Moreover, the strategies for improvement of building maintenance will be determined.

2.1 Definition of Building Maintenance

From the point of view of Khalid *et al.* (2019), the term building maintenance refers to a standard that has been established to maintain, improve, or restore each facility. According to Adejimi (2005), the objectives of building maintenance is to maintain the building in initial structural, functional, and aesthetic states, in resulting increase value to the building for a better market price. Moreover, building maintenance able to extend the life span of a building, ensuring health and safety of a building to the occupants. In many countries, building maintenance is turning into a serious problem as the number of older buildings increases (Islam, *et al.*, 2021).

2.2 Types of Maintenance

There are two types of maintenance, which is planned maintenance and unplanned maintenance. Planned maintenance is maintained on a schedule based (Ofori, Duodu, and Bonney, 2015). On the other hand, unplanned maintenance is often of an emergency or unpredictable situation (Olanrewajau, *et al.*, 2015). Figure 1 illustrates the maintenance types.

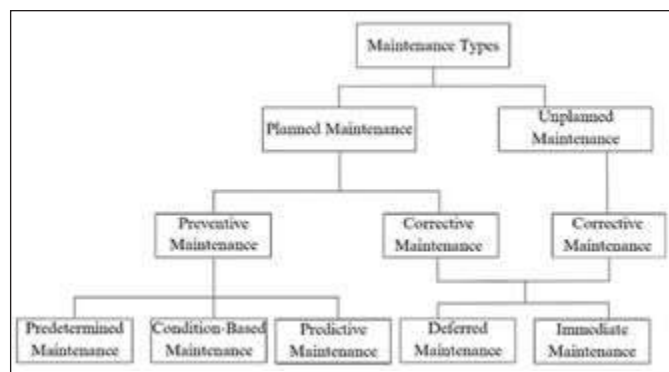


Figure 1: Maintenance types

2.2.1 Preventive Maintenance

A preventive maintenance is the replacement of the building parts based on the schedule, and the work can be carried out before the occurrence of a failure (Waziri & Vanduhe, 2013). Activities of preventive maintenance include replacements, adjustments, and lubrications. For instance, replace the door locks or hinges every 5 years whether the lock able to function or not. Eti, *et al.* (2006) stated that the main purpose of preventive maintenance is to maximise the reliability and extend the life of the components. In addition, the implementation of preventive maintenance able to reduce the need of corrective maintenance, as a result, reduce the repair cost (Au Yong, Ali,

and Ahmad, 2014). Preventive maintenance can be subdivided into three types, which are predetermined, condition-based, and predictive maintenance. Predetermined maintenance, also known as scheduled maintenance, which the activities is carried out at a fixed time interval according to the condition of the components. Next, condition-based maintenance is performed to monitor the condition of the component such as cost and availability regularly. While predictive maintenance is to measure the degradation of the components and carried out the maintenance activities before the expected failure time (Sarhini, *et al.*, 2021).

2.2.2 Corrective Maintenance

A corrective maintenance is carried out after the failure is identified and is aimed at restoring an asset back to a condition in which it can perform its intended function. It can be implemented in both planned maintenance and unplanned maintenance. In planned maintenance, a building component able to function until failure occurs. On the other hand, unplanned maintenance occurs when the building components fail to function in emergency and unpredictable situation (Sarhini, *et al.*, 2021). The failure normally caused by the inappropriate installation, poor design or poor materials (Ofori, Duodu, and Bonney, 2015). Corrective maintenance is subdivided into two types, which are deferred maintenance and immediate maintenance. Deferred maintenance is a set of maintenance activities that are not immediately initiated and delayed due to limitations such as cost, materials, and labour. Whereas immediate maintenance is implemented instantly to avoid damage (Sarhini, *et al.*, 2021).

2.3 Factors Affect Building Maintenance

Building maintenance is crucial to retain the functionality of the building, particularly as the building age over time. Also, building maintenance acts as a role in improving to enhance the building to meet the requirements and expectations of its occupants. However, inadequate building maintenance practices continue to persist in Malaysia due to various factors.

2.3.1 Inappropriate Material Selection

One of the key factors that leads to the early deterioration of building components is selection of the substandard and defective materials. The durability, strength, cost, and aesthetic appeal are frequently reflected in the quality of a material (Waziri, 2016). In the design phase of a building, choosing the appropriate material can minimise the maintenance requirements in the future (Islam, *et al.*, 2021).

Besides, the quality of the material can be affected by the environment (Olanrewaju, *et al.*, 2015). Malaysia is a tropical country which has rainfalls and high humidity all year round. The buildings have to exposed to the sunlight, wind and rain, which mean that the external components of the building will be deteriorated if using the inappropriate materials (Ahzahar, *et al.*, 2011). For example, paintwork on the external walls normally peeled off due to the excessive weather in Malaysia (Tan & Md Azree, 2013). Therefore, it is important to select the paint which can withstand the extreme weather in a time frame of 5 years.

2.3.2 Poor Workmanship

Construction industry is a labour-intensive. Therefore, construction workers play a main role in providing a high-quality of building to minimise the building maintenance works, from the start to the end of the project (Olanrewaju, *et al.*, 2015). According to Tan and Md Azree (2013), a poor workmanship can worsen the quality and performance of a building, such as poor construction method. Besides, a poorly designed foundation design might cause ground movement, which would be visible as fractures in the brick walls, a change in the building, and may even a sagging roof and many more (Hassan, *et al.*, 2016).

2.3.3 Poor Design

According to the Olanrewaju, *et al.* (2015), the buildings designed without considering the maintainability aspect will lead to difficulty in maintenance. When designing or constructing a building, the maintenance aspect needs to be considered to ensure that the maintenance can be performed with minimum cost and time (Olanrewaju, *et al.*, 2015).

Poor design can be categorised as defects in civil drawings, architectural drawings, and construction drawings (Waziri, 2016). The two essential factors in the construction process that affect the life cycle of a building are design and maintenance (Kiong and Akasah, 2012). Most of the client would like to minimise the project cost during the design phase. The common design errors are reducing the size of column, reinforcement bar, and foundations. These will cause to uncertainty in the future as the structure may unable to withstand the load, in resulting lead to building failure (Ahzahar, *et al.*, 2011).

2.3.4 Poor Supervision

One of the contributions to the factor affects building maintenance is poor supervision. A poor supervision can lead to construction defects, which caused to a poor-quality of building. Numerous causes of construction defects may be obvious to the naked eye or hidden deep within the structure (Waziri, 2016). Supported by Waziri (2016), the construction defects generally are caused by the design do not meet the professional standard and code. Construction defects normally can lead to structural defects, inadequate of drainage system, inadequate fire protection systems and many more, which are resulting in increasing of the complexity of the building maintenance (Meor Hasan, *et al.*, 2016). Such construction defects can lead to a poor-quality of project delivery.

According to earlier research by Okuntade (2014), adequate monitoring will reduce the majority of building faults, resulting in minimising the building maintenance throughout operation. Therefore, a quality of site supervision during the construction stage has a huge influence on the performance of the project (Dalibi, 2016). The experience and knowledge of a site supervisor is important to provide the high-quality of construction projects. A site supervisor who lacks the knowledge and required experience in supervision may cause to a building require constant maintenance (Waziri, 2016).

2.3.5 Lack of Maintenance Culture

In the Malaysian construction industry, the lack of preventive building maintenance still exists and resulting in poor building

maintenance (Au Yong, Ali, and Ahmad, 2014). This issue may happen due to a poor maintenance culture and a lack of knowledge of building maintenance. Maintenance culture is the way of thinking, perception, behaviour, values, and the basic assumptions of any person, group, or society that considers that maintenance is important (Abiodun, Olayemi, and Joseph, 2016). When a person, group, or society has the maintenance culture, they will have the actions and attitudes to maintain, protect and preserve the facilities, which can lengthen the lifespan of the building. On the other hand, a poor maintenance culture can lead to shorten a building's lifespan (Waziri, *et al.*, 2013). Therefore, by adopting the preventive maintenance work able to help in lengthening a building's lifespan.

2.3.6 Designer's Responsibility

A designer plays a main role in minimising the maintenance practice requirement when come to the operation. The responsibility of a designer is to make sure the expectations and requirements are met during the design phase and reflected during the construction phase (Islam, *et al.*, 2021). Supported by Chohan *et al.* (2010), the designers are often unaware of the effects of their design decisions until the POE. For example, an irregular architectural shape of a building cause difficulties when comes to maintenance work (Islam, *et al.*, 2021).

A designer has to consider several issues during the design phase, such as the climatic, environment, local culture and many more. According to Olanrewaju, *et al.* (2015), buildings are exposed to the sunlight, rain, wind, and humidity. The responsibility of the designer is to design the building correctly and selecting the appropriate material to be constructed to reduce the time and cost of the maintenance work in the future. For example, a flat roof might inappropriate to be constructed in the tropical countries such as Malaysia due to the heavy rainfalls and high humidity, and it will be resulting in the high amount of maintenance cost.

2.4 Post Occupancy Evaluation (POE)

In recent years, Malaysia has experienced an incredible rise in the population and urbanisation. Former Housing and Local Government Minister Zuraid Kamaruddin stated that 386,340 affordable housing units are planned, while 181,211 units are currently under development (New Straits Times, 2020). PPR is one of the affordable housing programmes introduced by the Malaysian government to assist low-income groups and squatters. Safety performance and physical environment of the housing are always the concern for the residents. Therefore, the environmental and quality issues become an important aspect to emphasise when developing low-cost housing projects (Nurhayati, *et al.*, 2015).

POE, is a method to demonstrate the significant aspects of the evaluation, while the main consideration is to define the building and the participation required from the occupants such as feedback (Husin, *et al.*, 2015). As indicated by Chohan *et al.* (2010), related to the relationship between the satisfaction of the occupants with architectural aspects of housing, the majority of researchers agreed on the significance of resolving problems with design defects, building maintenance, and satisfaction of the occupants. Besides, the finding conducted

by Mohit and Azim (2012) supported that the satisfaction of the residents more influenced by the services provides, such as maintenance, availability of public facilities and so on.

2.4.1 Building Performance

Building performance has a closely integrated with the users, as the users will measure the performance levels of the building which might impact on the customer satisfaction level and building occupancy rates. A building which fulfils the requirements of comfort, healthy, safe and high-quality able to attract building users and impact the supply and demand of building stock. Therefore, building performance is crucial in ensuring that the high-quality assets can achieve the satisfaction and requirements of the users (Wahab & Kamuruzzaman, 2011).

PPR is aimed to provide affordable housing for the low-income groups and improve living condition. However, PPR has labelled as poor maintenance, high vandalism and crime rates. Thus, building performance plays a main role in serve as a measurement to monitor the operation and condition of the building and act as a guideline for further improvements (She, Aini, & Zyed, 2022).

The aspects that will be analysed in the building performance by POE technique are the condition, performance in term of maintenance, and safety of the building. This is to ensure that the building overall has meet the requirements and satisfaction of the residents.

2.4.2 Physical Environment

The physical environment describes the circumstances and external factors in people's life that affect their health (Live Well San Diego, 2014). The physical environment of the neighbourhood, including its air quality, noise levels, interior amenities, and other factors, has a substantial impact on the residents' well-being and health (Live Well San Diego, 2014). Therefore, the physical environment has an impact on the level of satisfaction of the occupants based on their opinions, perceptions, and evaluations of environmental elements including building density, design, and location (Nurhayati, *et al.*, 2015).

According to the analysis by Nurhayati, *et al.* (2015), dwelling unit features are one of the main factors that influence the physical environment of the community. For instance, the size of the living room, the size and number of bedrooms, size of toilets and bathrooms. As stated by The Sun Daily (2023), the children living in PPR are unhappy and stressed as they do not have enough spaces and facilities for them to study and play; in resulting they faced mental problems. Hence, the designer plays a crucial role in ensuring the size of the dwelling unit fix the residents' requirements. Moving forward, the analysis by Mohit, Ibrahim, and Rashid (2010), figured out that the social environment received the lowest satisfaction from the occupants. This is due to the location of the public low-cost housing being far away from the hospital, LRT stations, and public library. Most of the residents prefer to shorten the traveling time to the public goods and workplace (Said and Juanil, 2013). Furthermore, a study by Sulaiman, Hasan, and Jamaluddin (2016) indicated that most of the occupants are unsatisfied with the services of refuse disposal and becomes

a major issue among the occupants as lead to affect the occupants' quality of living life. Thus, the physical environment is vital to provide a quality living life to the occupants.

In physical condition, there are several elements that will be analysed by using the POE technique. For example, the exterior finishes, interior finishes, quality of the material used, quality of the workmanship, satisfaction on the dwelling size and services of the management. Inadequate material selection can cause to building deterioration over time. For example, using non-waterproof resistant wall finishes as external finishes can increase the wear and tear on the walls. Moreover, the lack of preventive maintenance, such as the delay of sealing cracks detected can lead to water infiltration, in resulting brings the damages to the walls and foundations over the time.

2.4.3 Safety Performance

The safety performance assessment is one of the significant conditions for judgment in the satisfaction of the functionality and the requirements of occupants. (Husin, *et al.*, 2015). As stated by The Star (July 23, 2009), the occupants of low-cost housing in Desa Mentari, Petaling Jaya, expressed safety concerns and complained about holes beneath concrete slabs, uneven ground, and the roof's failure. These indicated that the poor design, poor workmanship and inappropriate material selection are the factors causing to the building failure. Besides, Goh and Yahaya (2011) indicated that when adjustable louvered windows are installed, there is a risk that the glass panes' catches are malfunctioning and will fall from the higher floor, leading to safety concerns for the occupants. Therefore, the lack of the preventive maintenance by the management is the factor that leading the residents' concern and worries on the issues.

2.5 Strategies to Improve Building Maintenance

The involvement of each relevant stakeholder, including the building owners, tenants, maintenance team, and many more plays an integral role to share the responsibility for solving these challenging issues to foster a harmonious living environment for PPR's residents. An excellent maintenance practice can affect the satisfactory of the residents, in resulting creating a harmonious living environment to the residents (Masyatul, 2013).

2.5.1 Regular Training in Construction Industry

According to Waziri (2016), to achieve the project's goals, the construction labours must be knowledgeable and skilled when performing the construction works. Therefore, outstanding training is necessary for having high-quality construction. This is due to the labours can improve their construction knowledge when attending the training. All parties involved in the construction process, including the clients, must receive ongoing training on the job site to share information and reduce construction defects (Dantew and Enday, 2019).

2.5.2 Involvement of the Organisation's Maintenance Experts

The involvement of maintenance departments is one of the strategies to improve building maintenance. The activities covered by the maintenance departments are cleaning services, repairs, planned maintenance and corrective

maintenance (She, Aini, and Zyed, 2022). The maintenance departments should create a method for evaluating the building that establishes the minimal criteria standards at which various buildings should be maintained (Awol, Adugna, and Mosisa, 2016). An excellent building maintenance practice able to maintain the building at the initial stage and effectively serves its purpose (Masyatul, 2013).

The maintenance departments can conduct maintenance operation plan, which to identify the maintenance activities to carry out in a timely manner (Awg and Amin, 2013). This action will bring a huge confidential to the residents. Next, a Post Occupancy Evaluation (POE) can be carried out to evaluate and review on the requirements and expectations from the residents.

2.5.3 Strict Supervision

In construction industry, it is often suffering from the poor performance in terms of delays, cost overruns and poor-quality projects (Dalibi, 2016). A poor-quality project can affect the performance, profitability, and the reputation of the organisation involved (Dalibi, 2016). For example, a poor-quality activity can lead to costly rework or building failure, in resulting to project delays, cost overruns, and injuries. Such poor-quality project is linked to the poor supervision. Therefore, a strict supervision on construction sites is a vital criterion to enhance the quality of the projects (Razak, *et al.*, 2010).

Firstly, Public Works Department (PWD) plays an important role in monitoring and inspecting construction activities during the construction stage to ensure strict compliance with the design and specifications (Tan and Md Azree, 2013).

Construction industry is a labour-intensive, which the quality of the building is depends on the performance of the workmen (Dalibi, 2016). Within the construction site, the implementation of strict supervision plays a vital element. The quality of the building is depending on the performance in the construction site. Nevertheless, contractors or subcontractors should engage in daily oversight so that any issue related to the quality of labour can be found and fixed immediately (Hassan, *et al.*, 2016). The inability of supervisors in planning of work and miscommunication are linked to the poor-quality project delivery (Dalibi, 2016). Therefore, it is crucial to have experienced and well-trained site supervisors to monitor and inspect during the construction stage.

2.5.4 Proper Communication Among Parties

Communication is the key to leading a project to success. For instance, a supervisor has to deliver a message or information to the workers, so, the workers will carry out the work correctly when received the correct message. If one of the parties delivers or receives the wrong messages, it will lead to negative consequences such as construction failure. Therefore, a proper communication between individuals and organisations to increase the quality of design, workmanship, and construction (Danitew and Enday, 2019).

2.5.5 Proper Construction Management

Construction management is knowns as the comprehensive planning, coordinating, and oversight of a construction project from inception to completion. The main categories will

be investigated are cost, scope, schedule, safety, and risk management (Go Codes, 2023).

A project cost budget is important as it covers from the start to end of the project, such as labour cost, plant and machinery, material and equipment (Go Codes, 2023). However, construction industry is complex as it may consist of some unpredictable concerns such as increasing price of raw materials, extreme weather, and unforeseen diseases. Therefore, a proper construction management can help in reducing the risk by control budget, scheduling, and problem solving (Go Codes, 2023).

Also, the quality of workmanship can be improved by proper construction management (Dantew and Enday, 2019). A main contractor or site supervisor has responsible to manage, organise and lead the work. The proper construction management can directly affect the productivity of the labours (Meor Hasan, *et al.*, 2016). For instance, if a main contractor or site supervisor failed to control and lead the project, the issue regarding the quality of the project will occur.

2.5.6 Proper Manpower Management

Construction productivity primarily depends on human effort and performance (Meor Hasan, *et al.*, 2016). A proper manpower management able to ensure the cost-effective of a project (Majumdar, 2023). Manpower management ensure that the appropriate workers are placed in the appropriate roles, based on their skills and knowledges. If a project consists of improper manpower management such as insufficient numbers of workers, it may cause the work to be in a rush and result in poor quality of the project (Dantew and Enday, 2019). For example, the contractor has to keep track of the workload done every day, to ensure that the manpower management is sufficient. Also, manpower management helps in controlling project's cost. This is due to a proper manpower management can avoid hiring over workers, which can cause in increasing of labour cost (Majumdar, 2023). Hence, proper manpower management is crucial in a construction project to ensure the cost-effective of a project.

3.0 METHODOLOGY

A quantitative research approach has been chosen to fulfil the research objectives of this research. The central focus of this research is to enhance the building maintenance of PPR, ultimately fostering a harmonious living environment for its occupants. Within the confines of this study, an exploration into the requirements, expectations, and satisfaction of PPR's occupants is intended. According to Pajo (2018), the utilisation of extensive samples can be used to reflect the perceptions of broader populations. A huge portion of opinions and viewpoints from respondents becomes imperative to bolster the precision of information. Consequently, a quantitative research methodology is chosen due to its capacity for extensive data compared to the qualitative research method. Moreover, its efficiency in gathering data is particularly pertinent given the time constraints in this study. A questionnaire survey is distributed among PPR's occupants in Kuala Lumpur. Subsequently, the data collected will undergo rigorous examination through the Statistical Package for Social Science (SPSS) software tool.

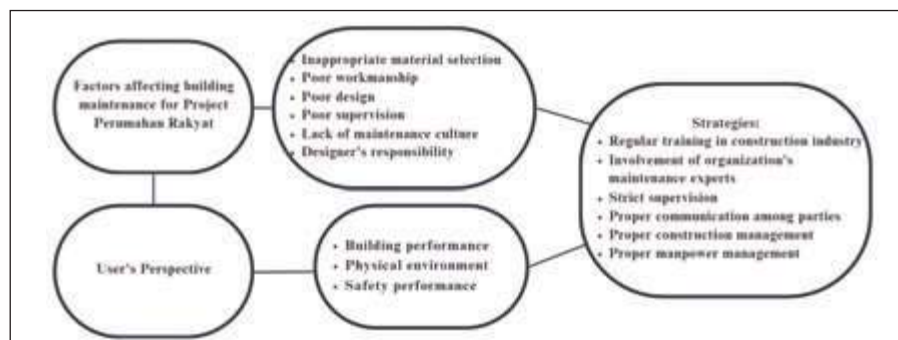


Figure 2: Theoretical framework of the study

since it takes less time to complete for respondents. Additionally, respondents can complete the online survey on a mobile device, laptop, or tablet with no time or geographical restrictions. The higher the sample size, the higher the reliability of this study. Figure 3 illustrates the information about the PPR in Kuala Lumpur comes with the sample size.

3.4 Data Analysis using SPSS

Data analysis helps solve search-related issues by using numbers and facts

3.1 Theoretical Framework

This study reviewed the critical factors that affect residential building maintenance for PPR. The utilisation of Post Occupancy Evaluation (POE), valuable insight into the effectiveness and efficiency of the maintenance practices from the perspectives of the users can be gained. Figure 2 illustrates the theoretical framework of this study.

3.2 Data Collection

A large amount of information is required to be gathered when implementing a quantitative research method. To come up with an accurate result, being careful in collecting data and information is necessary. In this study, the online distribution of questionnaire surveys is more appropriate to gather a huge portion of responses in a short time. The target population is the occupants who live in PPR, Kuala Lumpur.

3.3 Questionnaire Distribution

The questionnaire surveys were distributed electronically through social media such as email, Facebook, WhatsApp to the occupants who live in PPR, Kuala Lumpur. Online surveys typically have greater response rates than paper surveys

(Ashiwadam, 2020). Consequently, the researchers were able to understand the relevance of the research-based technique, including statistical significance related to the research topic, and to gain a greater understanding of data analysis. The data collected from the questionnaire were interpreted and further analysed by using SPSS software. Moreover, the statistical tests that will be used in this chapter include Cronbach's Alpha Reliability method and Measures of Central Tendency.

4.0 RESULTS AND DISCUSSION

In this section, the relative results from the findings of the factors affecting residential building maintenance for PPR from the user's perspective in Kuala Lumpur are presented. Besides, a Post Occupancy Evaluation (POE) regarding on building performance, physical environment, and safety performance is reviewed among PPR's residents. Also, the strategies for improving building maintenance are evaluated from the respondents based on responses. The data were collected through an online questionnaire survey and will be analysed using Statistical Package for Social Science (SPSS) software.

4.1 Descriptive Analysis

Total of 380 sets of respondents is received through social media such as email, WhatsApp, and Facebook. The target respondents are the residents who live in PPR, Kuala Lumpur. The details of the respondents are summarised and tabulated in the Table 1.

4.2 Cronbach's Alpha Reliability Test

A total of 380 respondents' feedback was calculated and analysed by Statistical Package for Social Science (SPSS) accordingly. Table 2 shows the result of reliability test obtained for the factors, POE, and strategies were 0.906, 0.962, and 0.901. According to the Cronbach's Alpha, the greater the value is, the more reliable the sample is. Therefore, the Cronbach's Alpha value of obtained in Table 4.2 are excellent result because the values are ranged beyond 0.900. Hence, the data collected are highly reliable to be used for analysis.

4.3 Mean Ranking

The mean values are analysed by using the Statistical Package for Social Science (SPSS) software. After that, the relative ranking of each item is arranged by following the individual mean scores. The mean score and ranking are computed and presented in Tables 3, 4, 5, 6, and 7.

No.	Housing Projects	Total No. of Units	Total No. of Blocks	Handover Year	Sample Size(s)
1	PPR Pekan Batu	632	2	2002	20
2	PPR Desa Petaling	632	2	2002	20
3	PPR Pudu Hulu	948	3	2003	30
4	PPR Seri Anggerik	316	1	2003	20
5	PPR Seri Alam	660	5	2004	30
6	PPR Salak Selatan	632	2	2004	20
7	PPR Laksamana & PPR Perkasia	1,620	5	2005	30
8	PPR Seri Semarak	1,580	5	2005	30
9	PPR Kg Limau	632	2	2005	20
10	PPR Kg Mhibbah	2,844	9	2006	30
11	PPR Raya Permai	1,264	4	2006	30
12	PPR Seri Malaysia	632	2	2007	20
13	PPR Kg Baru Air Panas	2,528	8	2007	30
14	PPR Pantai Ria	1,264	4	2007	30
15	PPR Pekan Kepong	948	3	2010	20
TOTAL		17,132	57	-	380

Figure 3: Information on PPR, Kuala Lumpur

Table 1: Demographic of respondents

	Percentage (%)	Respondent (N=165)
Gender		
Male	52	197
Female	48	183
Age Range		
21-30 years	35	134
31-40 years	31	116
41-50 years	23	86
51-60 years	8	32
Above 60 years	3	12
Marital Status		
Single	44	168
Married	38	143
Divorced	18	69
Number of Family Members Living with the Respondent		
1-2	38	144
3-5	25	132
Above 5	27	104
Period Living in PPR of Respondent		
Less than 1 year	11	41
2-5 years	19	71
6-10 years	51	194
11-15 years	15	58
More than 15 years	4	16
Satisfaction Level of Respondents with the Building Maintenance in PPR		
Very Unsatisfied	5	19
Unsatisfied	6	22
Neutral	9	33
Satisfied	48	184
Very Satisfied	32	122

Table 2: Cronbach's Alpha Value of Reliability Test

Sections	Cronbach's Alpha	Cronbach's Alpha Based on Standardised Items	N of Items
Factors affecting residential building maintenance	0.906	0.916	6
Post Occupancy Evaluation (POE)	0.962	0.962	50
Strategies to improve in building maintenance	0.901	0.905	6

Table 3: Mean Ranking of Factors Affecting Residential Building Maintenance

Code	Factors	Means	Ranking
F1	Inappropriate Material Selection	4.28	1
F2	Poor Workmanship	4.22	2
F3	Poor Design	4.19	3
F4	Lack of Maintenance Culture	4.15	4
F5	Designer's Responsibility	4.08	5
F6	Poor Supervision	3.95	6

4.3.1 Factors Affecting Residential Building Maintenance

Table 3 present the mean ranking of the factors that affect the residential building maintenance, and the level of agreement based on the perspectives of residents who living in PPR, Kuala Lumpur. The highest mean ranking indicates that the respondents believed that a factor is more likely to affect the building maintenance.

As shown in Table 4.3, the factor with the highest mean ranking of 4.28 was 'Inappropriate material selection (F1)', which most of the respondents strongly agreed was a major factor in affecting building maintenance. According to Ofori, Duodu, and Bonney (2015), poor quality of material will lead to failure of materials, which require replacement or more maintenance work in the future. Supported by Islam, *et al.* (2021), the appropriate material during the design phase is able to reduce the needs of maintenance in the future. Therefore, the selection of material during the construction stage is important to minimise the maintenance work in the future.

The second-highest mean ranking was 'Poor workmanship (F2)', with a mean value of 4.22. In the construction industry, skilled workers are important in performing a good quality of work (Ofori, Duodu, and Bonney, 2015). This is because skilled workers able to perform the work based on their skills and past experiences. It helps reduce the work time span, minimising cost and improving the quality of work. In comparison, unskilled workers required to spend more time in training, and additional money.

The lowest mean ranking among the factors was 'Poor supervision (F6)', which has a mean value of 3.95. The quality of the supervision depends on the skill of site supervisor (Dalibi, 2016). This is because the site supervisor is responsible for controlling and planning the construction work. As a site supervisor, communication is an essential skill which can affect the performance of construction (Hong, Wee, and Omar, 2021). For example, if the site supervisor gives insufficient information and instructions to the site workers, it will affect the progress of the construction performance. However, this key factor might not be the first priority among the residents based on the analysis result above.

Table 4: Mean Ranking of Post Occupancy Evaluation (Building Performance)

Code	Building Performance	Means	Ranking
A1	I agree that the building provides a sense of safety.	4.12	1
A3	I agree that the overall performance of the building, in terms of maintenance services, is good.	4.04	2
A2	I agree that the condition of the building, both inside and outside, is good.	3.94	3

4.3.2 Post Occupancy Evaluation (POE)

Table 4 indicates the mean ranking of building performance in Post Occupancy Evaluation. Most of the respondents agreed that the building provides a sense of safety, which has a mean value of 4.12. However, there is a mean value of 3.94 of the respondents agreed the condition of the building, both inside and outside is good.

Table 5 showed the mean ranking of physical condition in the Post Occupancy Evaluation. The highest mean ranking value is 4.18, which indicated that the majority of the respondents satisfied the internal floor finishes of the building. The second highest mean ranking value is 4.17, which most of the respondents satisfied on the internal ceiling finishes of the building. While the third highest mean ranking value is 4.16, which is the quality of the ceiling finishes material.

Table 5: Mean Ranking of Post Occupancy Evaluation (Physical Condition)

Code	Physical Condition	Means	Ranking
B6	I agree that the interior finishes (floor finishes) of the building are good.	4.18	1
B4	I agree that the interior finishes (ceiling finishes) of the building are good.	4.17	2
B7	I agree that the quality of ceiling finishes material is good.	4.16	3

Table 6 shows the mean ranking of the safety performance in Post Occupancy Evaluation. Most of the respondents were satisfied on the functionality and responsiveness of the fire alarms in the building, which showed a mean value of 4.09. The second-highest of the mean ranking value is 4.08, which most of the respondents were satisfied on the lighting system in the stairwells and lobby area.

Table 6: Mean Ranking of Post Occupancy Evaluation (Safety Performance)

Code	Physical Condition	Means	Ranking
C21	I agree that the functionality and responsiveness of fire alarms in the building is good.	4.09	1
C18	I agree that the lighting system in the stairwells area is good.	4.08	2
C16	I agree that the lighting system in the lobby area is good.	4.08	2

4.3.3 Strategies to Improve Building Maintenance

Table 7 provided the mean scores and ranking of the strategies to improve building maintenance. A higher mean score represented that the strategies are effective in improving building maintenance from the perspective of the respondents.

Based on Table 7, the highest mean ranking is 'Regular training in construction industry (S1)', with a mean value of 4.29. Hanuashdh, Jailani, and Rahman (2021) outlined that work performance might be affected by the lack of training. For instance, a supervisor who lacks knowledge in controlling the maintenance operational framework will lead to a poor-quality maintenance outcome. In contrast, a skilled team able to perform a professional level of work, which produce a good quality of work.

The second-highest mean ranking is 'Involvement of organisation's maintenance experts (S2)', with a mean value of 4.23. According to Rodrigues, *et al.* (2018), the lack of preventive maintenance will fasten the deterioration of buildings. The organisation's maintenance experts play an important role in conducting preventive maintenance, such

as, checking on the functionality of rainwater gutters, lighting system in the common area, servicing mechanical and electrical installation. Therefore, the restoration or major repair can be avoided or postponed. Besides, the collaboration of the organisation's maintenance experts between stakeholders is important to ensure that the building maintenance to success (Au-Yong, *et al.*, 2017).

The lowest mean ranking among the strategies was 'Strict supervision (S6)', with a mean value of 3.98. According to Hong, Wee, and Omar (2021), a strict supervision able to ensure the quality of building. It helps to increase the disciplinary and adapt good practices of the construction workers in the work. Hence, strict supervision during the construction stage can minimise the delivery of poor-quality of work. However, based on the analysis results above, most of the residents might not consider that strict supervision able to help in improving building maintenance. This is due to the strict supervision might bring drawbacks such as decreased morale of the workers which can lead to a decrease in productivity.

Table 7: Mean Ranking of Strategies to Improve Building Maintenance

Code	Strategies	Means	Ranking
S1	Regular training in construction industry	4.29	1
S2	Involvement of organisation's maintenance experts	4.23	2
S3	Proper communication among parties	4.22	3
S4	Proper construction management	4.20	4
S5	Proper manpower management	4.07	5
S6	Strict supervision	3.98	6

3.0 CONCLUSIONS

The aim of this research study is to enhance the building maintenance of PPR, which provide a harmonious living environment for the residents. However, the poor building maintenance still practices in Malaysia and lead to the increasing of building deterioration. Therefore, the research objectives such as factors that affect building maintenance, Post Occupancy Evaluation (POE), and the strategies to improve building maintenance are successfully achieved and reviewed.

The research contributes to the developers and contractors who engaged in construction industry. In this research, the factors affecting to the building maintenance had been identified, which provides a valuable information for the professionals. The developers and contractors can implement the strategies to improve the building maintenance. Moreover, this research has significant implications to local government bodies. Therefore, the local government may aware to the factors affecting to the building maintenance of PPR. A comprehensive understanding of the factors affecting building maintenance provides local governments with the tools to formulate policies and allocate resources. Hence, this research study enables local government bodies to take specific actions in improving the building maintenance and enhancing the quality of the PPR's residents.

There are several limitations are identified. Firstly, time constraint is one of the limitations faced by the research studies. Therefore, the study is restricted to conduct the data collection in Kuala Lumpur due to the time constraints. This led to the research study having a smaller sample size because of a lower number of data collection. As a result, the outcomes obtained may cause to inaccurate to represent the PPR's residents of whole Malaysia. Next, the data collection method implemented in this research is quantitative method. The quantitative method only provides numerical descriptions rather than comprehensive elaboration as compared to qualitative method. However, some of the respondents may provide simplistic answers to the questionnaire without thoroughly analysing the questions. Thus, this may lead to inaccuracies in the data collection.

There are a several recommendations suggested to solve these limitations. Firstly, lengthen the period for data collection. Therefore, the rate of respondents will increase and the data analysed will be more accuracy. Besides, expanding the research scope able to produce a higher accuracy and reliability result. Instead of restricting the study to Kuala Lumpur, the research should broaden the research area to the whole Malaysian state. This is important because the residents in other PPR may offer a different perspective on the building maintenance. As a result, expanding the research scope to include various Malaysian states will contribute to a more accurate and reliable research study. Also, a mixed research method is suggested to be implemented for the future studies to enhance the reliability and accuracy of data collection. A qualitative method, such as face-to-face interviews, able to facilitate in-depth and comprehensive explanations from respondents. This approach is able to mitigate the risk of simplistic answers encountered in questionnaire survey and increasing the confidence level in this research. ■

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PROFILE



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FROM BLUEPRINT TO GREENPRINT: SMART TECHNOLOGIES POWERING SUSTAINABLE CONSTRUCTION IN MALAYSIA

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Abstract

This study investigates the role of smart technologies in supporting sustainability management within Malaysian construction projects and identifies the key drivers influencing their adoption among primary stakeholders. Addressing a research gap in how digital innovations are prioritised and implemented for sustainability, the study collected 101 valid responses representing clients, consultants, and contractors. Descriptive statistical analysis using mean scores identified Building Information Modelling (BIM), Additive Manufacturing, and the Internet of Things (IoT) as the top-ranked technologies. The consensus across stakeholder groups highlights a shared recognition of these technologies' significance. Key adoption drivers include cost reduction, process optimisation, and increased stakeholder awareness. This study is timely, given the urgent need for the construction industry to adopt green practices in tandem with digital transformation, ensuring it remains competitive with other sectors. The findings offer valuable insights for practitioners and policymakers to strategically advance smart sustainable practices, aligning environmental goals with digital innovation. The study contributes incremental knowledge to Malaysian construction and offers broader implications for contexts seeking to integrate smart technologies in pursuit of a more sustainable and efficient future.

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1.0 INTRODUCTION

Sustainability has become a central concern across various sectors, including the construction industry, which is well known for its significant environmental, social, and economic impacts. Broadly defined, sustainability refers to the capacity to maintain development over time in a way that meets present needs without compromising the ability of future generations to meet theirs (Mollenkamp 2025). In support of this vision, the United Nations introduced the Sustainable Development Goals (SDGs) to encourage practices that harmonise economic development with environmental protection and social equity (Fei *et al.* 2021).

The construction industry is a major driver of global economic activity, valued at approximately USD 1.7 trillion and contributing between 5 to 7 per cent of global Gross Domestic Product (GDP) (Alaloul *et al.* 2021). In Malaysia, the sector continues to play a pivotal economic role. In the second quarter of 2024, strong construction activity supported a 5.9 per cent year-on-year GDP expansion (CIDB Malaysia 2024). This upward trend continued into the first quarter of 2025, where the construction sector recorded a remarkable 14.2 per cent growth, contributing significantly to Malaysia's overall GDP growth of 4.4 per cent (Malaysian Ministry of Finance 2025). This robust performance reflects sustained infrastructure development

and aligns with the government's MADANI framework, which promotes high-quality investments and pro-development policies. Importantly, the framework also underscores the need for sustainable economic growth, positioning the construction sector as a key player in advancing green construction practices and supporting national commitments to environmental stewardship and climate resilience.

In line with Malaysia's push towards digital transformation, the Construction 4.0 Strategic Plan (2021–2025) by CIDB Malaysia provides a national roadmap for modernising the industry through the adoption of emerging technologies (CIDB 2020). This includes the transition from automated production to a greater level of digitalisation, with the integration of cyber-physical systems (CPS) that connect physical construction processes with digital intelligence. These technologies are revolutionising traditional construction by enabling real-time data exchange, autonomous operations, and advanced analytics, thus driving a new era of modernisation for humanity. Such transformation supports modernisation efforts by enhancing productivity and driving sustainable, data-driven construction outcomes (Forcael *et al.* 2020; Lekan *et al.* 2021). Despite its vital economic contribution and technological progress, the construction industry faces growing scrutiny due

to its significant environmental impact. It is a major source of greenhouse gas emissions, consumes large volumes of natural resources, and generates substantial construction and demolition waste (Yap *et al.* 2024a).

To address these challenges, sustainable construction has gained prominence. Sustainable construction involves the application of environmentally responsible and resource-efficient processes throughout a building's lifecycle, from design to deconstruction (Kibert 2022). This concept is grounded in the "triple bottom line" framework, which emphasises balancing economic viability, environmental responsibility, and social equity (Nogueira *et al.* 2025). Thus, sustainability encompasses not only reducing environmental harm but also promoting cost efficiency and social inclusivity in project development.

More recently, the convergence of sustainability and technological advancement has introduced a new dimension: smart sustainable practices. These involve integrating digital technologies - such as Building Information Modelling (BIM), the Internet of Things (IoT), artificial intelligence, and advanced data analytics - to improve sustainability performance in construction projects. Smart sustainable practices enable real-time monitoring and resource optimisation, helping reduce environmental impacts and improve project efficiency and outcomes (Mohamed *et al.* 2024).

Within Malaysia, initiatives like the Green Building Index (GBI), the promotion of Industrialised Building Systems (IBS), and strategic plans by the Construction Industry Development Board (CIDB) reflect a growing institutional commitment to sustainability. Although the Construction Industry Transformation Programme (CITP) 2016 to 2020 laid a strong foundation in areas such as environmental sustainability and productivity, it has since concluded. The latest strategic direction under CIDB's Construction Strategic Plan 2021 to 2025 continues to emphasise sustainability, with a greater focus on environmental resilience, digital integration, and green construction practices aligned with national development goals. However, the utilisation of smart technologies to support sustainable development remains uneven and underexplored locally. While many technologies are available, their adoption and integration into sustainability frameworks still lack consistency, industry-wide coordination, and comprehensive documentation.

Current research often addresses sustainability initiatives or technological innovation separately, missing the opportunity to explore their combined benefits (Chan *et al.* 2019; Olawumi and Chan 2020). Furthermore, much of the literature is international, with limited focus on Malaysia's unique policy environment, industry practices, and contextual factors. The lack of localised insight limits stakeholders in formulating effective strategies to promote smart sustainable practices.

Achieving sustainability goals in construction requires more than simply having advanced technologies. It depends fundamentally on the enabling conditions that drive their adoption, such as institutional support, regulatory frameworks, organisational capacity, and stakeholder engagement (Saka *et al.* 2020; Ferdosi *et al.* 2023). These drivers influence how effectively digital innovations contribute to environmental performance, operational efficiency, and long-term project sustainability. As Malaysia pursues a green and digital future

through frameworks such as the MADANI economic narrative, the Construction 4.0 Strategic Plan (CIDB 2020), and the Construction Industry Transformation Programme (CITP) (CIDB 2015), the integration of smart technologies becomes essential to achieving strategic national and government-aligned sustainability objectives.

However, the adoption of smart sustainable technologies is often hindered by contextual barriers such as high upfront costs, limited digital literacy, fragmented project delivery systems, and resistance to change (Durdyev *et al.* 2018; Oke *et al.* 2021; Ogunsanya *et al.* 2022). These constraints can weaken or delay adoption efforts, especially when enabling conditions are unclear or misaligned. Therefore, identifying and strengthening the right set of adoption drivers is crucial to overcoming these challenges and accelerating the uptake of smart sustainability practices.

Given these considerations, this study aims to explore the types of smart sustainable practices that have the potential to support sustainability management within the Malaysian construction industry and to identify the key drivers encouraging their adoption. By examining these technologies and the underlying motivators, the research seeks to contribute to the advancement of smart sustainability in construction, providing valuable insights for industry practitioners, policymakers, and researchers striving to align Malaysia's construction activities with national and global sustainability objectives. This study addresses two primary research questions:

1. What smart technologies can potentially support sustainability management in Malaysian construction projects?
2. What are the key drivers encouraging the adoption of these smart sustainable practices?

2.0 LITERATURE REVIEW

2.1 Triple Bottom Line and Sustainability

Sustainable Development (SD) is commonly framed through the Triple Bottom Line (TBL) concept, which encompasses three pillars: economic, social, and environmental sustainability (Khan *et al.* 2021; Nogueira *et al.* 2025). These pillars correspond to profit (traditional financial performance), people (social responsibility), and planet (environmental stewardship). For true sustainability, these dimensions must progress in harmony, as all three are essential (Evans *et al.* 2017).

Economically, smart technologies offer benefits such as reduced labour and material costs, increased productivity and flexibility, shortened setup times, and improved customer satisfaction (Witkowski 2017; Dalenogare *et al.* 2018). Environmentally, digital tools enable energy optimisation, waste reduction, and carbon footprint tracking, while facilitating product reuse, recycling, and remanufacturing (Bai *et al.* 2020). Socially, technologies like wearables enhance worker health and safety, while automating repetitive tasks to improve job satisfaction (Bai *et al.* 2020).

The United Nations' 2030 Agenda for Sustainable Development, embodied in the 17 Sustainable Development Goals (SDGs), further supports the TBL framework by addressing economic growth, social equity, and environmental protection globally. These goals set concrete targets - such as

reducing poverty, ensuring health, education, and gender equality - that construction industries can align with to contribute meaningfully to sustainable development worldwide.

2.2 Definition of Smart Sustainability

Smart sustainability refers to the application of technologies aimed at enhancing sustainability across multiple dimensions, including energy management, material utilisation, waste reduction, cost savings, and the health and well-being of communities. As shown in Table 1, sustainability encompasses not only environmental factors but also economic and social aspects by creating economic opportunities and fostering

resilient societies. Simply put, smart sustainability integrates the concepts of ‘smart’ and ‘sustainable’ within the construction industry to enable more digitalised and environmentally friendly construction methods. The use of technology in construction seeks to improve economic performance, minimise the environmental impacts associated with traditional construction processes, and deliver benefits to local communities and their surroundings. In light of this, smart sustainability serves as a strategic conduit for integrating sustainability goals with advanced digital technologies. The rapid advancement of transformative technologies - such as artificial intelligence (AI), machine learning (ML), data analytics, and the Internet of Things (IoT - collectively known as exponential technologies, offers significant potential to accelerate progress toward achieving the SDGs (Pan and Nishant 2023). Table 1 summarises various definitions of smart sustainability as proposed by different authors.

Table 1: Definition of smart sustainability

No.	Definition of Smart Sustainability	References
1	“The organisational activities that seek to advance the sustainable development goals through creative deployment of technologies that create, use, transmit, or source electronic data.”	(George <i>et al.</i> 2021, p. 1000)
2	“Developing so-called high technologies for implementation in various areas of economic activity allow us to apply the principles of sustainable development in an intelligent manner”	(Radziejowska & Sobotka 2021, p.1)
3	Introducing technologies into the processes to improve economic gains and to minimise the environmental impact in delivering construction products and services.	(Prebanić & Vukomanović 2021)
4	“Developing smart grids and putting in place smart and green technologies are given high priority across Europe, in order to reduce carbon emissions, achieve future goals of sustainability, and assure electric stability to cities and their citizens.”	(Biresselioglu <i>et al.</i> 2018, p. 418)

2.3 Smart Sustainable Practices in Construction Industry

The construction industry is currently experiencing and adapting to the changes brought about by the Fourth Industrial Revolution. This revolution has led to the adoption of new technologies, from which the construction industry has also benefited. The term Construction 4.0, first introduced by Roland Berger, encompasses digitalisation in construction processes. It incorporates four key concepts: digital data, digital access to data, improved connectivity, and automation of machines (Forcael *et al.* 2020). Construction 4.0 further consists of a framework of three main components: the integration of digitalised technologies, industrial manufacturing and construction, and a cybersecurity system (Sawhney *et al.* 2020).

Table 2: Literature map for smart sustainable practices in construction industry

Ref	Smart sustainable practices	References												Total			
		(Forcael <i>et al.</i>)	(Sacks <i>et al.</i> 2018)	(Craveiro <i>et al.</i>)	(Osunsanmi <i>et al.</i>)	(Lekan <i>et al.</i> 2021)	(Kor <i>et al.</i> 2023)	Tahmasebinia <i>et al.</i>	(Turner <i>et al.</i> 2021)	(Liu <i>et al.</i> 2022)	(Wangler <i>et al.</i>)	(Li <i>et al.</i> 2019)	(Wang <i>et al.</i> 2020)		(Arowoija <i>et al.</i> 2020)	(Li <i>et al.</i> 2018)	(Qureshi <i>et al.</i> 2020)
P1	Building information modelling	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓		10
P2	Additive manufacture / 3D printing	✓		✓	✓	✓	✓		✓	✓							7
P3	Internet of things (IoT)	✓					✓	✓				✓	✓	✓	✓		7
P4	Sensors			✓				✓				✓	✓	✓			5
P5	Augmented reality (AR) / virtual reality (VR)	✓			✓	✓									✓		4
P6	Artificial intelligence / machine learning	✓					✓						✓		✓		4
P7	Cloud computing				✓	✓									✓		3
P8	Global positioning system					✓						✓		✓			3
P9	Big Data	✓			✓												2
P10	Blockchain										✓					✓	2
P11	Robotics			✓			✓										2
P12	Automation			✓													1

Industrial production and construction under this framework include 3D printing, additive manufacturing, prefabrication, automation, and other off-site construction methods that reduce on-site labor. These processes often integrate with Building Information Modelling (BIM), enabling construction professionals to transmit digital instructions for physical production. In terms of cyber-physical systems, automation technologies - such as actuators, sensors, and the Internet of Things (IoT) - are deployed to transform digital signals into physical actions across production, transport, and assembly stages.

Furthermore, digital technologies critical to Construction 4.0 include laser scanning, blockchain, big data and analytics, augmented reality (AR), and artificial intelligence (AI). A key enabler for these technologies is the Digital Ecosystem, which refers to interconnected IT resources functioning collectively as a unified system (Brush 2023). These innovations provide construction companies with opportunities to enhance quality and competitiveness.

Table 2 presents a literature map summarising various smart sustainable practices identified in the construction industry. According to the literature, BIM and IoT are among the most frequently adopted technologies to support sustainability goals and enable data-driven decision-making (Forcael *et al.* 2020). Other practices such as 3D printing, sensors, AR/VR, AI/ML, and cloud computing also contribute significantly to the smart and sustainable transformation of the sector.

2.4 Key Drivers for Smart Sustainable Practices to be used in Construction Industry

The construction industry is under increasing pressure to adopt smarter and more sustainable approaches in response to environmental degradation, rising operational costs, and evolving stakeholder expectations. Within this context, numerous studies have investigated the factors that drive the implementation of smart sustainable practices in construction. A prominent and widely acknowledged driver is the potential to reduce construction costs. Researchers such as Opoku *et al.* (2022), Badamasi *et al.* (2022), and Won *et al.* (2022) have highlighted cost savings as a key motivation for adopting smart technologies, as these tools can help streamline processes, minimise material waste, and improve resource utilisation. These economic advantages are particularly relevant in developing countries like Malaysia, where cost efficiency remains a central concern for both public and private sector projects.

Table 3 presents a comprehensive literature map summarising the key drivers that influence the adoption of smart sustainable practices in the construction industry. According to this table, the most frequently cited driver is the potential for reduced construction costs, referenced by eight different sources. This indicates strong scholarly consensus on the economic benefits of smart technologies.

In addition to cost reduction, the optimisation of construction processes has emerged as another important driver. Technologies such as Building Information Modelling (BIM), Internet of Things (IoT), and data analytics are increasingly being used to improve project scheduling, workflow coordination, and supply chain efficiency. Authors such as Khan *et al.* (2021) and Olanrewaju *et al.* (2022) argue that these smart

solutions help mitigate common industry challenges such as delays, rework, and coordination failures. Through enhanced integration of planning and execution stages, smart practices allow stakeholders to gain greater control over project delivery, contributing to improved overall performance. This driver is also strongly supported in Table 3, appearing in seven of the reviewed studies.

Improved health and safety is another consistently identified incentive for the adoption of smart sustainable practices. The construction sector is inherently high-risk, with frequent incidents related to site hazards, equipment misuse, and human error. Smart systems such as real-time monitoring devices, wearable sensors, and predictive safety analytics have shown promise in reducing accidents and enhancing worker wellbeing. Studies by Saka *et al.* (2020) and Yap *et al.* (2022), emphasise that incorporating safety-focused technologies not only supports regulatory compliance but also builds a safer working environment, which can translate into long-term cost and reputation benefits for firms. As shown in Table 3, this driver was also highlighted in seven publications.

Stakeholder awareness has further been recognised as a fundamental driver. Raising awareness among clients, consultants, and contractors about the benefits and practicalities of smart sustainable practices is essential to overcoming resistance to change. The works of Olawumi and Chan (2020) and Yap *et al.* (2023) stress the importance of education, training, and industry dialogue in promoting a more forward-thinking mind-set. When stakeholders are well-informed about the value and applicability of these innovations, they are more likely to advocate for their use and embed them into standard practice. This driver is reflected in five sources in Table 3.

Financial capacity is another critical factor influencing adoption. While smart technologies can deliver long-term returns, the initial investment can be substantial. Saka *et al.* (2020) and Yap *et al.* (2024) argue that the availability of financial resources determines whether firms are willing and able to invest in new systems. This financial preparedness is often linked to company size, client support, and access to funding schemes. Hence, financial incentives, subsidies, or targeted support from government and industry bodies may serve as catalysts for wider adoption. Table 3 also supports this point, showing "Adequate financial resources" cited in four studies.

Additional drivers such as enhanced energy management, higher productivity, and improved decision-making are also gaining traction in the literature. Energy management, in particular, is essential in meeting carbon reduction goals and complying with green certification requirements. Improved data availability and analytics allow decision-makers to assess performance metrics in real time, enabling more responsive and sustainable project management. Although some drivers - such as top management support, which appears in only one source in Table 3 - are less frequently cited, they remain crucial to ensure strategic alignment and organisational commitment.

In summary, Table 3 illustrates a diverse and interconnected set of drivers - ranging from cost and productivity gains to awareness, funding, and environmental concerns - that collectively shape the adoption of smart sustainable practices in the construction industry. Understanding these drivers is

essential for stakeholders aiming to accelerate the digital and sustainable transformation of the sector.

2.5 Gaps of Knowledge

Although sustainability and technological advancement have become central themes in global construction discourse, their integration within the Malaysian construction industry remains limited and underexplored. While policies and initiatives such as the Green Building Index and the Construction Industry Transformation Programme demonstrate a growing commitment to sustainable development, the adoption of digital innovations that enhance sustainability outcomes - such as Building Information Modelling, the Internet of Things and artificial intelligence - remains inconsistent. Existing studies often examine sustainability and smart technologies separately, overlooking their combined impact and potential to improve project performance.

This gap is particularly significant given the increasing environmental pressures, resource constraints and rising demands for social equity within the construction sector. The industry must reduce its ecological footprint while meeting expectations for cost-effective and inclusive development. Smart sustainable practices that use digital technologies to optimise resources, reduce waste and support data-driven decision making offer a promising way to meet these challenges. However, empirical research on how these practices are currently applied, especially in the Malaysian context, is scarce. Furthermore, little is known about the key factors motivating primary stakeholders - clients, consultants and contractors - to adopt such innovations. Addressing these gaps is essential to fostering a more sustainable and technologically advanced construction industry in Malaysia.

3.0 RESEARCH METHODOLOGY

This study adopts a pragmatic research paradigm, which is well-suited for addressing complex real-world issues by focusing on solutions that work in practice (Creswell and Clark 2011). Pragmatism supports methodological flexibility and emphasises the practical consequences of research, making it particularly relevant to applied fields such as construction management, where the integration of sustainability and technology demands both theoretical insight and practical implementation (Sherratt *et al.* 2025). A quantitative research approach was employed to examine current trends in smart sustainable practices and to identify the key drivers influencing their adoption. This approach aligns with prior research, including Olawumi and Chan (2020), who investigated the drivers of smart sustainable practices in Hong Kong, Yap *et al.* (2024b), who examined the benefits of sustainable procurement in the Malaysian construction industry and Darko *et al.* (2018), who explored factors influencing the adoption of green building technologies in Ghana. The pragmatic orientation of the study facilitates flexible methodological choices aimed at bridging the gap between theory and practice, particularly within the context of sustainable construction development.

The research process commenced with an extensive review of the literature to conceptualise smart sustainable practices and to identify potential drivers for their adoption. This review guided the development of a structured questionnaire, which was designed to collect empirical data from key industry stakeholders - namely clients, consultants, and contractors - across various organisations in Malaysia. The questionnaire consisted of Likert-scale items aimed at gauging respondents' perceptions of the relevance and importance of identified practices and drivers.

Table 3: Literature map for drivers to smart sustainable practices in construction industry

Ref	Drivers	References														
		(Opoku et al. 2022)	(Badamasi et al. 2022)	(Saka et al. 2020)	(Windapo 2014)	(Won et al. 2022)	(Häkkinen and Belloni 2011)	(Khan et al. 2022)	(Olanrewaju et al. 2022)	(Chan 2014)	(Kivits and Furneaux 2013)	(Olawumi and Chan 2020)	(Antón and Díaz 2014)	(Eadie et al. 2013)	(Olsson et al. 2019)	Total
D1	Reduced construction costs	✓	✓	✓		✓		✓					✓	✓	✓	8
D2	Optimised construction process	✓	✓					✓	✓	✓	✓			✓		7
D3	Improved health and safety	✓	✓		✓	✓				✓				✓	✓	7
D4	High awareness of stakeholders			✓	✓		✓					✓	✓			5
D5	Adequate financial resources			✓			✓				✓				✓	4
D6	Enhanced energy management	✓						✓			✓		✓			4
D7	Higher productivity			✓				✓	✓							3
D8	Enhanced decision making	✓							✓							2
D9	Reduced time for overall design process	✓												✓		2
D10	Improved environmental monitoring	✓							✓							2
D11	Sustainable data management					✓				✓						2
D12	Top management support			✓												1

The collected data were analysed using the Statistical Package for the Social Sciences (SPSS). Mean scores were calculated to prioritise both the smart sustainable practices currently observed and the key drivers facilitating their adoption. Higher mean values indicate stronger agreement or perceived importance among respondents (Olawumi and Chan 2020). To determine whether statistically significant differences exist in the perceptions among different respondent groups (clients, consultants, and contractors), the Kruskal-Wallis (KW) test was applied. This non-parametric method is suitable for comparing three or more independent groups and does not assume a normal distribution (Yap *et al.* 2024b), making it appropriate for ordinal data derived from Likert-scale responses.

This methodological approach enables a comprehensive understanding of the prioritised smart sustainable practices and the key factors driving their adoption within the construction industry. It also provides insights into variations in stakeholder perspectives, offering a nuanced view of industry readiness and alignment with sustainability goals in the Malaysian context.

3.1 Questionnaire Development

The questionnaire was structured into three distinct parts to facilitate a clear and comprehensive data collection process. The survey began with an introductory section that clearly explained the research objectives, ensuring that participants understood the purpose of the study. The first section gathered demographic information from respondents, including their role within the company, the nature of their construction-related business, years of professional experience, and highest level of educational attainment.

The second section sought respondents' views on the contribution of various technologies to sustainability management in construction. Participants rated each technology using a five-point scale ranging from "not at all significant" (1) to "extremely significant" (5). The final section concentrated on identifying key drivers encouraging the adoption of smart sustainable practices within the construction industry. Respondents evaluated twelve identified drivers using a five-point Likert scale, where 1 indicated the driver was perceived as "ineffective" and 5 as "very effective".

To confirm the questionnaire's clarity and reliability, a pilot test was conducted involving five participants representing key stakeholder groups: two main contractors, two consultants, and one developer. Feedback from this pilot was instrumental in refining the survey, leading to corrections in grammar, improved wording, and the removal of ambiguous items. Responses collected during this pre-test phase were not included in the main analysis.

3.2 Sampling and Data Collection

The research targeted construction industry stakeholders in Malaysia's Klang Valley, a key urban hub centred on Kuala Lumpur and known for its concentration of construction activities (Yasin *et al.* 2022). The focus was on construction professionals as the primary unit of analysis. To gather participants, a combination of convenience and snowball sampling techniques was used. Convenience sampling allowed the recruitment of readily available respondents, while

snowball sampling helped to broaden the participant pool by encouraging referrals within professional networks until no new information was obtained.

In total, 320 electronic questionnaires were disseminated through various digital platforms, including email, LinkedIn, and WhatsApp. To maximise participation, reminders were sent over a four-week period following the initial distribution. This method was intended to capture a diverse and representative sample, supporting the collection of robust and generalisable data for the study.

4.0 RESULTS AND DISCUSSION

4.1 Survey Participants and Demographics

Over a four-week period, 101 valid responses were obtained (see Table 4), resulting in a 31.68% response rate, which is acceptable for construction management research. The sample included 27 clients (26.7%), 34 consultants (33.7%), and 40 contractors (39.6%), ensuring balanced representation across key stakeholder groups. Nearly 60% of respondents had over ten years of industry experience, offering seasoned perspectives on construction practices.

In terms of roles, the majority were junior (59.4%) and senior executives (28.7%), with nearly 12% holding managerial and above positions. Academically, more than 70% had at least a bachelor's degree, including 8.9% with postgraduate qualifications. This mix of practical experience and academic background strengthens the credibility of insights regarding the adoption of smart sustainable practices in Malaysia's construction sector.

4.2 Prioritising Smart Technologies for Sustainability Management in Construction

Cronbach's alpha for the twelve assessed smart technologies was 0.821, exceeding the accepted threshold of 0.70 and confirming the internal consistency and reliability of the measurement scale (Olawumi and Chan 2020; Yap *et al.* 2024b). Mean scores and standard deviations were calculated based on responses to a five-point Likert scale evaluating the perceived importance of each smart technology in supporting sustainability management in the construction industry. Table 5 presents the results, ranked by mean score. In cases where two or more technologies shared the same mean, the technology with the lower standard deviation was prioritised, indicating greater consensus among respondents.

All twelve technologies achieved mean scores above 3.00, signalling general agreement on their relevance to sustainable construction practices. Building Information Modelling (BIM) (Mean = 4.94) and Additive Manufacturing/3D Printing (Mean = 4.90) emerged as the highest-rated technologies, reflecting widespread recognition of their transformative potential. They were followed by the Internet of Things (IoT) (Mean = 4.66), Sensors and Augmented/Virtual Reality (both Mean = 4.43), and Artificial Intelligence/Machine Learning (AI/ML) (Mean = 4.39), forming a top tier of perceived high-impact technologies.

The remaining technologies - Robotics, Automation, Cloud Computing, Big Data, GPS, and Blockchain - ranked lower but still scored between 3.10 and 4.01, indicating their

acknowledged relevance in advancing digital integration and sustainability in construction, albeit with relatively lesser influence.

Analysis by stakeholder group (developers, consultants, and contractors) showed overall agreement on the top five smart sustainable technologies: BIM, Additive Manufacturing, IoT, Sensors, and Augmented Reality/AI. However, contractors uniquely ranked Additive Manufacturing as the most significant, ahead of BIM, whereas consultants placed AI above Augmented Reality, contrasting with the preferences of developers and contractors.

Referring to Table 5, BIM is identified as the most impactful practice for sustainability in construction overall, with both developers and consultants concurring on its top ranking. This aligns with prior research highlighting BIM's role in enhancing economic, social, and environmental sustainability. For instance, Lekan *et al.* (2021) emphasise BIM's capacity to increase productivity and enable an integrative approach

supporting social sustainability, while Govindan *et al.* (2016) highlight BIM's contributions to time and cost efficiency aligned with sustainability objectives. Contractors, however, ranked Additive Manufacturing higher than BIM, likely due to less exposure to BIM software compared to developers and consultants. El-Sayegh *et al.* (2020) reported contractors' particular interest in on-site 3D printing applications, and Thurairajah and Goucher (2013) discussed BIM's benefits from cost consultants' perspectives, including clash detection and enhanced information sharing. Thus, BIM's advantages appear more directly realised by developers and consultants.

Sensors and Augmented Reality shared identical mean scores and standard deviations overall, indicating equal perceived contribution to sustainability following IoT. However, subtle differences exist among stakeholder groups: developers view Augmented Reality as slightly more impactful, contractors favour Sensors, and consultants rate Sensors on par with AI (Table 5).

Table 4: Respondent's demographic profile

Parameters	Categories	Respondents Group			Total	Frequency (%)
		Client	Consultant	Contractor		
Working experience	< 5 years	12	10	15	37	36.63
	6-10 years	8	15	14	37	36.63
	11- 15 years	4	5	8	17	16.83
	16-20 years	1	3	2	6	5.94
	> 20 years	2	1	1	4	3.96
Position	Junior Executive	19	21	20	60	59.41
	Senior Executive	5	8	16	29	28.71
	Manager	2	4	3	9	8.91
	Senior Manager	1	1	1	3	2.97
	Top Management	0	0	0	0	0
Academic Qualification	SPM / High School	0	0	0	0	0
	Diploma	9	12	7	28	27.72
	Bachelor's Degree	16	19	29	64	63.37
	Postgraduate Degree	2	3	4	9	8.91

Table 5: Mean and ranking of smart sustainable practices

Ref	Smart sustainable practices	Overall (N=101)			Client (N=27)			Consultant (N=33)			Contractors (N=41)			Chisquare	Asymptotic significance
		Mean	S.D	Rank	Mean	S.D	Rank	Mean	S.D	Rank	Mean	S.D	Rank		
P1	Building information modelling	4.9406	0.2765	1	4.9630	0.1925	1	4.9697	0.1741	1	4.9024	0.3745	2	0.860	0.650
P2	Additive manufacturing/ 3D printing	4.9010	0.3002	2	4.9259	0.2669	2	4.8788	0.3314	2	4.9024	0.3004	1	0.368	0.832
P3	Internet of things (IoT)	4.6634	0.5706	3	4.6667	0.5547	3	4.7273	0.4523	3	4.6098	0.6663	3	0.286	0.867
P4	Sensors	4.4257	0.5540	4	4.4074	0.5724	5	4.3939	0.4962	4	4.4634	0.5957	4	0.580	0.748
P5	Augmented reality (AR)/ virtual reality (VR)	4.4257	0.5540	4	4.5556	0.5064	4	4.3333	0.4787	6	4.4146	0.6315	5	2.683	0.262
P6	Artificial intelligence/ machine learning	4.3861	0.5093	6	4.3704	0.5649	6	4.3939	0.4962	4	4.3902	0.4939	6	0.005	0.998
P11	Robotics	4.0099	0.4358	7	3.9630	0.4369	8	4.0909	0.3844	7	3.9756	0.4737	7	1.699	0.428
P12	Automation	3.9901	0.4582	8	4.0000	0.4804	7	4.0303	0.4667	8	3.9512	0.4448	8	0.560	0.756
P7	Cloud computing	3.7030	0.6090	9	3.6667	0.5547	9	3.6970	0.5855	9	3.7317	0.6717	9	0.218	0.897
P9	Big data	3.3069	0.5957	10	3.3333	0.6202	10	3.3030	0.5855	10	3.2927	0.6018	10	0.396	0.821
P8	Global positioning system	3.1980	0.5481	11	3.1852	0.5573	11	3.2424	0.6139	11	3.1707	0.4951	11	0.170	0.919
P10	Blockchain	3.0990	0.5001	12	2.9630	0.5175	12	3.1515	0.5075	12	3.1463	0.4775	12	4.939	0.085

Interestingly, automation and robotics, initially ranked lower, are now regarded more favourably by respondents, at 7th and 8th positions respectively. Pan and Zhang (2021) note that construction automation and robotics (CAR) are gaining global recognition as critical to the industry’s sustainable future and have developed methods to assess CAR’s sustainability impact. Nonetheless, Urrea and Kern (2025) caution that current robotics technologies still face challenges in precision and error correction, indicating ongoing development needs. Respondents’ elevated ranking of robotics and automation suggests growing industry acknowledgement of their potential to enhance sustainability outcomes. Conversely, blockchain technology was consistently rated lowest (12th), perceived as having the least direct contribution to sustainability in construction.

The Kruskal–Wallis test was applied to assess differences in technology perceptions across stakeholder groups. The results indicated no statistically significant differences ($p > 0.05$) among developers, consultants, and contractors, suggesting a consistent and homogeneous understanding of the importance of these smart technologies for sustainability management. This consensus reinforces the robustness of the findings and indicates a shared recognition within the Malaysian construction industry of the critical role digital tools play in driving sustainable practices.

4.3 Prioritising the Key Drivers of Smart Sustainable Practices

As part of the analysis, Cronbach’s alpha for the twelve evaluated drivers was recorded at 0.815, exceeding the accepted threshold of 0.70 and confirming the internal consistency and reliability of the scale (Olawumi and Chan 2020; Yap *et al.* 2024b). Mean scores and standard deviations (SD) were computed to prioritise the drivers, as presented in Table 5. All drivers achieved mean scores above 3.00, indicating general agreement among respondents regarding their importance in advancing smart sustainable practices within the Malaysian construction sector.

The results as presented in Table 6 reveal that the 1st ranked driver was *reduced construction costs* (Mean = 4.87), reflecting industry consensus that financial efficiency is a core motivator for smart sustainability adoption. According to Ogunbiyi and Goulding (2013) and Yap *et al.* (2024b), sustainable construction enhances cost savings while fostering innovation and competitiveness. Khan *et al.* (2022) highlighted that Modular Integrated Construction (MIC) can lead to cost savings of up to 20% through offsite manufacturing, while also reducing the likelihood of cost escalation across project phases. Furthermore, smart technologies reduce dependency on manual labour, lowering operational costs. As Shi *et al.* (2013) emphasised, cost-effectiveness should be considered from a lifecycle perspective rather than focusing solely on initial capital investment. Thus, the ability to reduce overall construction costs emerges as a compelling driver for the implementation of smart sustainable practices.

The 2nd ranked driver was *optimised construction processes* (Mean = 4.79), underscoring the perceived value of improved workflow efficiency. Langston and Zhang (2021) noted that methods such as prefabrication and lean construction contribute significantly to productivity and streamline operations from the early design phase. Efficient construction processes help shorten project timelines, thereby reducing total costs and supporting the traditional project management triangle of time, cost, and quality. For example, the use of Building Information Modelling (BIM) facilitates 4D visualisation of construction sequencing, enabling stakeholders to detect and resolve design clashes early, thereby reducing rework (Akponeware and Adamu 2017; Yap *et al.* 2022a).

The 3rd ranked driver was *improved health and safety* (Mean = 4.75), reaffirming the industry’s emphasis on worker well-being and social sustainability. This finding aligns with Durdyev *et al.* (2018), who placed health and safety among the top social drivers of sustainable construction. Smart technologies such as Augmented Reality (AR) and Virtual Reality (VR) can enhance on-site hazard identification and simulation training, as discussed by Li *et al.* (2018), thereby reducing accident rates and fostering a safer working environment.

Table 6: Mean and ranking to drivers of implementation

Ref	Drivers	Overall (N=101)			Client (N=27)			Consultant (N=33)			Contractors (N=41)			Chisquare	Asymptotic significance
		Mean	S.D	Rank	Mean	S.D	Rank	Mean	S.D	Rank	Mean	S.D	Rank		
D1	Reduced construction costs	4.8713	0.4618	1	4.9630	0.1925	1	4.8485	0.6185	1	4.8293	0.4417	1	2.672	0.263
D2	Optimised construction process	4.7921	0.4542	2	4.8519	0.3620	3	4.7273	0.5168	2	4.8049	0.4593	2	1.039	0.595
D3	Improved health and safety	4.7525	0.5551	3	4.8889	0.3026	2	4.7273	0.6742	3	4.6829	0.5674	3	2.618	0.270
D4	High awareness of stakeholders	4.4653	0.5963	4	4.4444	0.5064	4	4.6061	0.6586	4	4.3659	0.5812	4	4.773	0.092
D5	Adequate financial resources	4.3960	0.6013	5	4.4444	0.5037	5	4.3939	0.7882	5	4.3659	0.4877	5	0.823	0.663
D7	Higher productivity	4.2079	0.4758	6	4.2222	0.5064	6	4.3030	0.4667	6	4.1220	0.4580	6	2.553	0.279
D6	Enhanced energy management	4.1386	0.5662	7	4.1481	0.5338	7	4.1818	0.6826	7	4.0976	0.4902	7	0.930	0.628
D8	Enhanced decision making	4.1287	0.4830	8	4.1852	0.4833	8	4.1212	0.4846	8	4.0976	0.4902	8	0.428	0.807
D9	Reduced time for overall design process	3.9109	0.5495	9	4.0000	0.3922	9	3.9697	0.5855	9	3.8049	0.6008	11	2.798	0.247
D10	Improved environmental monitoring	3.8812	0.5155	10	4.0000	0.4804	10	3.8485	0.5658	10	3.8293	0.4951	9	2.002	0.367
D12	Top management support	3.8400	0.6624	11	3.8889	0.5774	11	3.8125	0.8206	11	3.8293	0.5875	10	0.417	0.812
D11	Sustainable data management	3.7228	0.5851	12	3.7778	0.6405	12	3.7273	0.5741	12	3.6829	0.5674	12	0.713	0.700

The 4th ranked driver was *high awareness of stakeholders* (Mean = 4.47). Stakeholder awareness is critical in driving the demand and support for smart sustainable practices. Oke *et al.* (2021) similarly ranked advocacy and awareness as key enablers for the adoption of sustainable construction. Olawumi *et al.* (2018) further stressed the importance of stakeholder knowledge and engagement in shaping project outcomes. With improved awareness, stakeholders are more likely to endorse and invest in smart and sustainable solutions.

The 5th ranked driver was *adequate financial resources* (Mean = 4.40), which highlights the foundational role of economic capacity in enabling the adoption of smart practices. Financial limitations are widely acknowledged as a barrier to sustainability implementation. Therefore, when adequate funding is available - particularly from clients - organisations are more willing to commit to sustainable technologies and strategies. Despite the potentially high initial investment in tools such as BIM and automation, these are offset by long-term cost savings, aligning with the benefits highlighted in the 1st ranked driver.

Lower-ranked drivers included *sustainable data management* (Mean = 3.72), *top management support* (Mean = 3.84), and *improved environmental monitoring* (Mean = 3.88). While still viewed positively, these were perceived to exert less influence relative to the top-ranked drivers.

Additionally, the Kruskal–Wallis test indicated no statistically significant differences in perceptions among the three stakeholder groups ($p > 0.05$), confirming consistent views across developers, consultants, and contractors. This alignment reinforces the robustness of the findings and highlights a unified industry perspective on the enablers of smart sustainable practices in the Malaysian construction context.

5.0 CONCLUSION

This study has provided valuable insights into the adoption of smart technologies that support sustainability management within the Malaysian construction industry. The findings reveal a clear prioritisation of key technologies, namely Building Information Modelling (BIM), Additive Manufacturing, and the Internet of Things (IoT), which are widely recognised by primary stakeholders as pivotal enablers of sustainable construction practices. Moreover, the consensus observed among clients, consultants, and contractors underscores a unified industry perspective on the importance of these technologies and the critical key drivers influencing their adoption, including cost reduction, process optimisation, and stakeholder awareness. Figure 1 presents the top three findings from this study, applying the Pareto principle (also known as the 80/20 rule).

This principle proposes that a small number of key factors are often responsible for the majority of outcomes. In this case, BIM, Additive Manufacturing, and IoT, together with their associated key drivers, are identified as contributing to approximately 80 per cent of the impact on smart sustainability adoption in the Malaysian construction industry.

The application of the Pareto principle is particularly important as it enables stakeholders to focus their efforts and resources on the most influential technologies and key drivers. Rather than dispersing attention across a wide range of lower

impact factors, this targeted approach allows for more effective strategic planning, decision making, and policy development. Prioritising high impact areas also supports stronger alignment with national sustainability objectives and facilitates a more efficient and scalable transition towards environmentally responsible and resilient construction practices. This strategic focus contributes to sustainability outcomes that reflect a balanced advancement of economic efficiency, environmental responsibility, and social well-being, driven by the effective adoption of smart technologies in the construction industry.

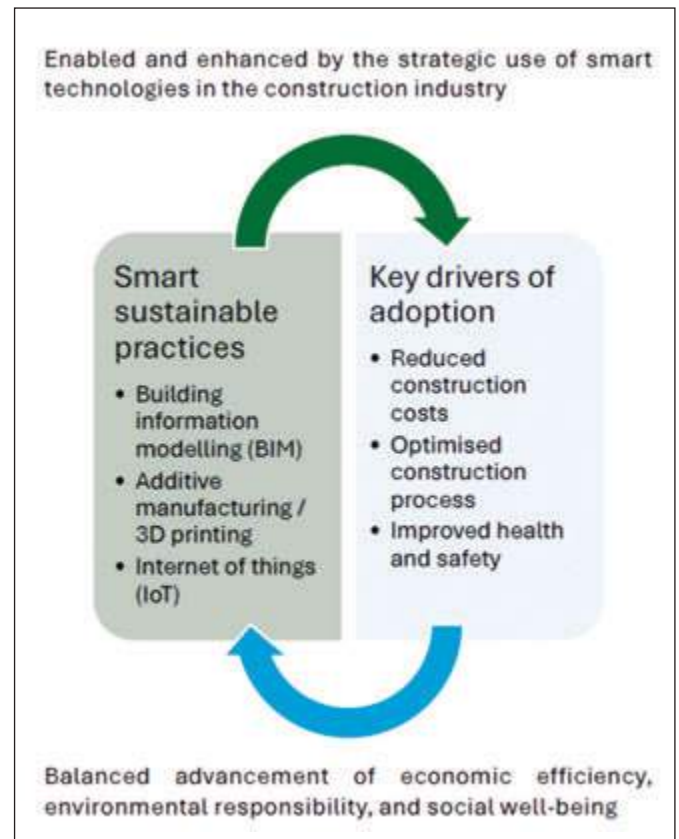


Figure 1: Priority technologies and adoption drivers in the Malaysian construction industry based on the Pareto principle

These results not only contribute incremental theoretical knowledge by contextualising smart sustainable practices within the Malaysian setting but also offer practical implications for industry practitioners and policymakers. By aligning digital transformation efforts with sustainability goals, the construction industry can accelerate its progress towards greener and more efficient project delivery. Encouraging the strategic adoption of these smart technologies can facilitate improved environmental performance, enhanced social well-being, and economic growth, thereby reinforcing the industry's commitment to sustainable development.

In an era where digital innovation is rapidly reshaping industries globally, the construction industry cannot afford to lag behind. This study highlights the timely imperative for embracing smart sustainable technologies as integral components of Malaysia's broader digital transformation agenda, ultimately supporting the transition to a greener and more resilient future.

6.0 RECOMMENDATIONS FOR THE MALAYSIAN CONSTRUCTION FRATERNITY

In alignment with the findings of this study and the strategic priorities outlined by the Construction Industry Development Board (CIDB) and national agendas such as the MADANI Framework - which emphasises sustainability and digital transformation as fundamental pillars for Malaysia’s future development - the following recommendations are proposed to accelerate the adoption of smart sustainable practices within the Malaysian construction industry:

i) **Accelerate Adoption of Smart Technologies to Drive Sustainability**

Prioritise the implementation of leading smart technologies - Building Information Modelling (BIM), Additive Manufacturing, and the Internet of Things (IoT) - to strengthen sustainability management in construction projects. These technologies facilitate improved resource optimisation, waste reduction, and enhanced environmental outcomes.

ii) **Leverage Key Adoption Drivers to Facilitate Digital Transformation**

Focus on critical drivers identified in this study, such as cost reduction, process optimisation, and heightened stakeholder awareness, to foster broader acceptance of smart sustainable practices. Tailored training programmes and awareness campaigns are essential to address resistance and bridge skill gaps.

iii) **Align Industry Practices with National Sustainability and Digitalisation Agendas**

Ensure integration of industry efforts with Malaysia’s MADANI Framework and initiatives including the Construction 4.0 Strategic Plan and National Construction Policy (NCP 2030) to advance a greener, more efficient construction sector. This alignment will promote policy coherence and unlock governmental support.

iv) **Enhance Collaborative Engagement Across Stakeholders**

Encourage strong collaboration among developers, consultants, contractors, and policymakers to secure shared understanding and commitment to sustainability objectives. Inclusive engagement fosters knowledge exchange and facilitates smooth adoption of new technologies.

v) **Invest in Capacity Building and Continuous Innovation**

Develop comprehensive, industry-wide programmes to upskill the workforce with emerging technologies and sustainable construction practices. Supporting ongoing innovation and research will sustain Malaysia’s competitiveness and underpin the transition towards a digital and sustainable construction future.

6.1 Limitations and Future Research

This study offers valuable insights into the prioritisation and adoption drivers of smart sustainable technologies within the Malaysian construction industry. However, the findings are based on responses from 101 participants representing primary stakeholder groups, which may limit the generalisability across the wider construction industry, particularly among smaller firms or peripheral actors. Future research could expand the sample size and include a broader range of stakeholders such as subcontractors, suppliers, and regulatory authorities to provide a more comprehensive perspective.

While the study identifies key drivers and prioritised technologies, it does not explore the barriers that may impede their practical adoption. Common challenges include the high upfront cost of implementation, especially for SMEs; limited digital literacy and skills shortages among the existing workforce; resistance to organisational change, often due to cultural inertia or fear of redundancy; and regulatory gaps or absence of supportive policy frameworks that hinder innovation uptake. These barriers can significantly slow down digital transformation despite recognised sustainability benefits.

Further qualitative or mixed method studies are recommended to explore these contextual obstacles in depth, which would provide a more grounded understanding of the implementation landscape. In addition, the cross-sectional nature of the data captures perceptions at one point in time. Longitudinal research could track how the prioritisation of smart technologies and adoption drivers evolve over time as sustainability mandates and digitalisation mature. Finally, since this research is specific to Malaysia, comparative studies with other countries would be valuable in examining how differing socioeconomic, cultural, or regulatory environments shape the adoption of smart sustainable practices in construction. Addressing these limitations will strengthen both the theoretical framework and practical application of smart technology adoption for sustainability management. ■

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AUTHORS’ CONTRIBUTIONS

Jeffrey Boon Hui Yap	Conceptualisation, study design, supervision, and writing – original draft.
Jeng Min Lim	Data collection, methodology, and formal analysis.
Ooi Kuan Tan	Writing – review and editing, and data interpretation.
Wun She Yap	Data validation, visualisation, and project resources.
Chee Fui Wong	Technical support, administration/project coordination, and investigation.

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IMPLEMENTATION OF ACTIVE-ANTI ROLL BAR CONTROL SYSTEM TO A 3-AXLE DOUBLE-DECKER BUS

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Abstract

Double-decker buses have the potential to save space in the traffic, but their center of gravity is high, which will cause a higher roll angle and discomfort to the passengers. In this paper, the existing control system of active anti-roll bars was tuned, implemented and modified specifically for double-decker buses. A full car ride and handling, 3-axle simulation model consisting of 20 degrees of freedom (DOF) was modeled and simulated within Matlab/Simulink environment. The controller proposed in this research is self-tuning fuzzy logic PID controller. A series of scenarios were tested, which are half bump, U-turn, double lane change (ISO3888-1) and moose test (ISO3888-2). For all the tests, main priority of performance improvement will be to focus on roll angle, roll rate, bounce motion and lateral acceleration. On average, active anti-roll bar (ARB) can improve the performance up to at least 90% compared to passive ARB, however lateral acceleration will be sacrificed by about 2.22% on average. Such small degradation on lateral accelerations performances on a double-decker bus will not affect safety negatively due to slower speed of the vehicle.

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1.0 INTRODUCTION

In developing countries like Malaysia, the population rate and the number of car owners have increased dramatically, which causes traffic problems to increase exponentially as well (Solah *et al.*, 2013). A high-deck double-decker bus has slowly been implemented by public transport company, which is a good solution for this situation. However, high deck double-decker buses are known to be dangerous as they are easy to cause accidents, more specifically rollover accidents (Solah *et al.*, 2013).

Rollover accidents are fatal to passengers and traffic around them, the cause of rollover accidents is due to lateral stability loss. Sided wind gusts, abrupt steering and braking maneuver by the driver are the three major factors for rollover accidents (Solah *et al.*, 2013; Gauchia *et al.*, 2010; Gillespie, 2021; Kuo & Li, 1999; Vu *et al.*, 2016; Vu, 2017). All these factors will cause one side of the vehicle wheel to leave off the ground and cause the normal force of tire and road to be zero when it reaches the threshold of roll angle, rollover accident starts. In this study, only abrupt steering input and its effects will be considered.

There are a few proposed methods to overcome body roll such as active steering control, which will affect the yaw motion to modify the rate of steering angle with a given different speed input. Other than that, active brake system will give a small brake force to each of the wheels (Gillespie, 2021; Vu *et al.*, 2016). Although this is a good method to keep every wheel

with the least slip angle to prevent understeer or oversteer and it also has the ability to detect a dangerous situation, the brake system will reduce the lateral tire force, which is responsible for the rollover (Gillespie, 2021; Vu *et al.*, 2016; Manap *et al.*, 2016). Next, active anti-roll bar is another advanced method to control excessive body roll, which usually pairs with hydraulic actuators, electric motor or pneumatic actuators to add or dissipate energy to the vehicle suspension system (Gauchia *et al.*, 2010; Gillespie, 2021; Vu, 2017; Muniandy *et al.*, 2015). When the center of gravity of the sprung mass is leaving the centerline, the sensors will detect the moment then by using the force of hydraulic actuators to react at the moment of vehicle body roll (Brian, 2002; Conover, 2004); this reaction will give the vehicle sufficient roll stiffness to stay flat relative to the road.

From the literature review, it can be concluded that active anti-roll bar (A.ARB) is suitable to be used to solve the problem of rollover accidents. The reason to eliminate the other two methods is that active steering control will also modify the desired path of the vehicle, affecting the yaw motion, and the active brake system will only activate when the wheel reaches nearly the limit of lift-off (Vu *et al.*, 2016; Noraishikin *et al.*, 2014). Both disadvantages mentioned could cause heavy vehicles to easily lose control and endanger the people around it. In this research, it is suggested to choose hydraulic linear actuators for the proposed A.ARB system due to the higher

force generation capability, suitable for heavy vehicles like double-decker bus (Brian, 2002; Conover, 2004; Noraishikin *et al.*, 2014).

To understand rollover events, according to (Vu, 2017), the rollover of heavy vehicles can be classified into four types, which are preventable, potentially preventable, non-preventable and preventable unknown. Although there are different types of rollover events with different levels of dangerous levels, the study shows that minority of rollover accidents could have been avoided with a warning device, but the majority were not preventable by driver action alone (Vu *et al.*, 2016; Vu, 2017). Because the rollover angle threshold is too small for the driver to feel the "vehicle is rolling", so the vehicle has already undergone rollover before the driver realises it (Vu *et al.*, 2016; Vu, 2017). According to Gillespie (2021), the rollover threshold is 5.886 m/s as for the base model that will be used in this paper, Enviro 500 double-decker bus. Since before this paper there are no specific 3-axle double-decker vehicle models presented in any literature, the author of this paper developed a new Full car 20 DOF mathematical model to simulate the 3-axle double-decker bus ride and handling motion. The details of the model will be explained in the next section.

2.0 RIDE AND HANDLING FULL 3-AXLE VEHICLE MATHEMATICAL MODEL

In this paper the author will modify and derive from existing 2-axle vehicle from (Gillespie, 2021; Muniandy *et al.*, 2015; Abu *et al.*, 2014; Darus & Yahaya, 2009; Frey, 2009; Ahmed, 2017; Joga *et al.*, 2009) to a new 3-axle vehicle mathematical model. In riding, comfort models consist of vehicle body roll, pitch and bounce motion with 6 vertical motions from the wheels resulting in 9 DOF. In handling model, it consists of vehicle body roll, pitch, lateral and longitudinal motion with 6 rotational motions from the wheels, resulting in 11 DOF. Full car, 3-axle mathematical model is the combination of the 2, therefore results in 20 DOF.

2.1 Ride Comfort Model for 3-Axle Full Vehicle (9DOF)

Figure 1 shows full car ride and handling model for 3-axle vehicle. Indication *i* and *j* will be used in this paper. Whereas *i* = 1, 2 and 3 for position of axle and *j* = 1 for left and 2 for right. The following equations will be derived based on Figure 1.

Vertical displacement and velocity equations for 3-axle vehicle

$$Z_{s11} = -\frac{w}{2}\phi_b + l_1\theta_b + Z_b \tag{1}$$

$$\dot{Z}_{s11} = -\frac{w}{2}\dot{\phi}_b + l_1\dot{\theta}_b + \dot{Z}_b \tag{2}$$

Where Z_{sij} is the vertical displacement of sprung mass on the location point of wheel, Z_b is the vertical displacement of body mass (center of gravity). α_b is the pitch angle of the vehicle, θ_b is the roll angle of the vehicle and L_i is the length of the axle to the centre of gravity. In equation 1 and 2, the term $\frac{w}{2}\phi_b$ and $\frac{w}{2}\dot{\phi}_b$ is negative at $j = 1$ and positive at $j = 2$, the term $l_1\theta_b$ and $l_1\dot{\theta}_b$ is positive at $i = 1$ and negative at $i = 2,3$.

Bounce motion for 3-axle vehicle

$$\ddot{Z}_b = \frac{1}{M}(C_{11}(\dot{Z}_{u11} - \dot{Z}_{s11}) + K_{s11}(Z_{u11} - Z_{s11}) + C_{12}(\dot{Z}_{u12} - \dot{Z}_{s12}) + K_{s12}(Z_{u12} - Z_{s12}) + C_{21}(\dot{Z}_{u21} - \dot{Z}_{s21}) + K_{s21}(Z_{u21} - Z_{s21}) + C_{22}(\dot{Z}_{u22} - \dot{Z}_{s22}) + K_{s22}(Z_{u22} - Z_{s22}) + C_{31}(\dot{Z}_{u31} - \dot{Z}_{s31}) + K_{s31}(Z_{u31} - Z_{s31}) + C_{32}(\dot{Z}_{u32} - \dot{Z}_{s32}) + K_{s32}(Z_{u32} - Z_{s32})) \tag{3}$$

Roll motion for 3-axle vehicle

$$\ddot{\phi}_b = \frac{1}{I_{xx}}(-C_{11}W_{11}(\dot{Z}_{u11} - \dot{Z}_{s11}) - K_{s11}W_{11}(Z_{u11} - Z_{s11}) + C_{12}W_{12}(\dot{Z}_{u12} - \dot{Z}_{s12}) + K_{s12}W_{12}(Z_{u12} - Z_{s12}) + T_{w1} - C_{21}W_{21}(\dot{Z}_{u21} - \dot{Z}_{s21}) - K_{s21}W_{21}(Z_{u21} - Z_{s21}) + C_{22}W_{22}(\dot{Z}_{u22} - \dot{Z}_{s22}) + K_{s22}W_{22}(Z_{u22} - Z_{s22}) + T_{w2} - C_{31}W_{31}(\dot{Z}_{u31} - \dot{Z}_{s31}) - K_{s31}W_{31}(Z_{u31} - Z_{s31}) + C_{32}W_{32}(\dot{Z}_{u32} - \dot{Z}_{s32}) + K_{s32}W_{32}(Z_{u32} - Z_{s32}) + T_{w3}) \tag{4}$$

Pitch motion for 3-axle vehicle

$$\ddot{\theta}_b = \frac{1}{I_{yy}}(-C_{11}l_1(\dot{Z}_{u11} - \dot{Z}_{s11}) - K_{s11}l_1(Z_{u11} - Z_{s11}) - C_{12}l_1(\dot{Z}_{u12} - \dot{Z}_{s12}) - K_{s12}l_1(Z_{u12} - Z_{s12}) + C_{21}l_2(\dot{Z}_{u21} - \dot{Z}_{s21}) + K_{s21}l_2(Z_{u21} - Z_{s21}) + C_{22}l_2(\dot{Z}_{u22} - \dot{Z}_{s22}) + K_{s22}l_2(Z_{u22} - Z_{s22}) + C_{31}l_3(\dot{Z}_{u31} - \dot{Z}_{s31}) + K_{s31}l_3(Z_{u31} - Z_{s31}) + C_{32}l_3(\dot{Z}_{u32} - \dot{Z}_{s32}) + K_{s32}l_3(Z_{u32} - Z_{s32})) \tag{5}$$

K_{sij} is the spring stiffness of the spring in sprung mass on each wheel, C_{ij} is the damping coefficient of the absorber in suspension on each wheel. Z_{uij} and Z_{sij} is the vertical displacement of unsprung and sprung mass, \dot{Z}_{uij} and \dot{Z}_{sij} is the vertical velocity of unsprung and sprung mass. M is the total mass of the vehicle I_{xx} is the moment of inertia about x-axis (roll axis), I_{yy} is the moment of inertia about y-axis (pitch axis) and \ddot{Z}_b is vehicle body bounce acceleration, $\ddot{\phi}_b$ is the vehicle body roll acceleration and $\ddot{\theta}_b$ is the vehicle body pitch acceleration. Figure 2 shows the free body diagram for an anti-roll bar.

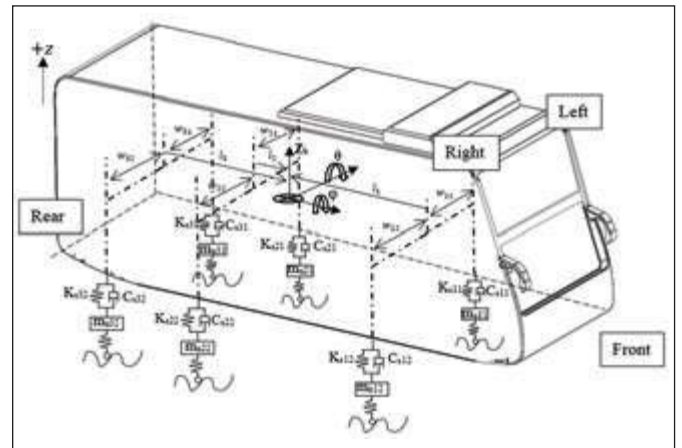


Figure 1: Ride comfort free body diagram for 3-axle vehicle

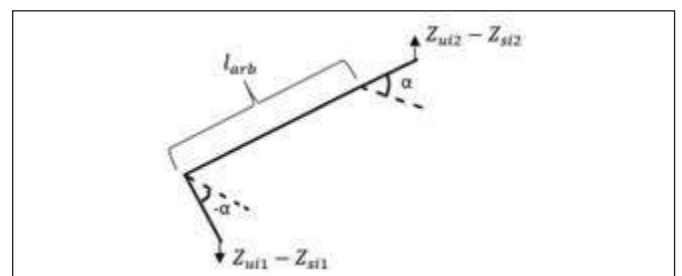


Figure 2: Free body diagram of anti-roll bar

Acceleration of unsprung mass for 3-axle vehicle

$$m_{uij}\ddot{Z}_{uij} = C_{ij}(\dot{Z}_{u1j} - \dot{Z}_{s1j}) + K_{sij}(Z_{u1j} - Z_{s1j}) - K_{rj}(Z_{r1j} + Z_{u1j}) - \left(\frac{K_{rj}}{W_{ij}}\right)\alpha \tag{6}$$

m_{uij} is the unsprung mass, \ddot{Z}_{uij} is the vertical acceleration of unsprung mass, K_{ij} is the tyre stiffness and K_{rj} is the passive anti-roll bar stiffness (P.ARB). The term $\left(\frac{K_{rj}}{W_{ij}}\right)\alpha$ negative at $j = 1$ and positive at $j = 2$.

2.2 Handling Model for 3-Axle Full Vehicle (11DOF)

By referring to Figure 3, yaw motion with aligning moment for 3-axle vehicle can be derived as follows:

$$I_{zz}\dot{\psi}_z = l_1(F_{x11} + F_{x12})\sin\delta + l_1(F_{y11} + F_{y12})\cos\delta - l_2(F_{y21} + F_{y22}) + \frac{m_s}{2}(F_{x12} - F_{x11})\cos\delta + \frac{m_s}{2}(F_{x22} - F_{x21}) + \frac{m_s}{2}(F_{y11} - F_{y12})\sin\delta - l_3(F_{y31} + F_{y32}) + \frac{m_s}{2}(F_{x32} - F_{x31}) + M_{z11} + M_{z12} + M_{z21} + M_{z22} + M_{z31} + M_{z32} \quad (7)$$

Where I_{zz} is the moment of inertia about z-axis, $\dot{\psi}_z$ is the angular velocity of yaw of the vehicle, l_i is the length from axle i to the centre of gravity, w_i is the width of the vehicle track and M_{zij} is the alignment moment.

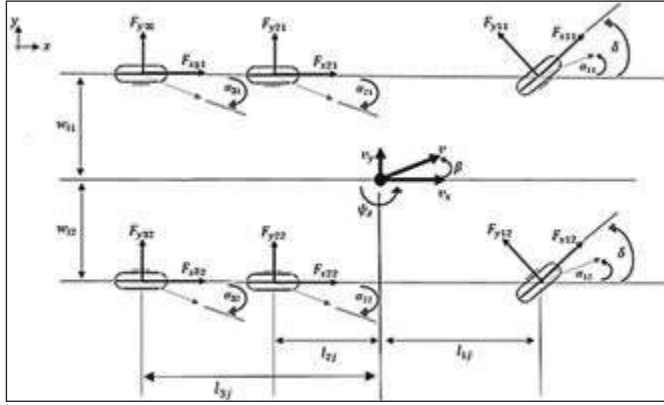


Figure 3: Free body diagram of planar of 3-axle vehicle

Longitudinal motion for 3-axle vehicle

$$a_x - v_y\dot{\psi}_z = \frac{1}{M}[(F_{x11} + F_{x12})\cos\delta - (F_{y11} + F_{y12})\sin\delta + F_{x21} + F_{x22} + F_{x31} + F_{x32}] \quad (8)$$

Where a_x is the acceleration of the vehicle in x-direction and v_y is the velocity of the vehicle in y-direction. ψ_z is the yaw angle of the vehicle and δ is the steering angle on the front wheels. F_{xij} and F_{yij} are forces on wheel in x and y direction. F_x is the longitudinal force on the wheel and F_y is the lateral forces on the wheel and δ is steering angle.

Lateral motion for 3-axle vehicle

$$a_y + v_x\dot{\psi}_z = \frac{1}{M}[(F_{y11} + F_{y12})\cos\delta - (F_{x11} + F_{x12})\sin\delta + F_{y21} + F_{y22} + F_{y31} + F_{y32}] \quad (9)$$

Where ψ_z is the yaw angle, a_y is the acceleration of the vehicle in y-direction and v_x is the velocity of the vehicle in x-direction.

Brake model for 3-axle vehicle

$$I_{\omega}\dot{\omega}_{ij} = T_{a ij} - T_{b ij} - F_{x ij}R_w \quad (10)$$

Where I_{ω} is the moment of inertia of the wheel about ω -axis. T_a and T_b are torque due to acceleration and torque due to braking. The F_f is the frictional force created between road and tyre. Lastly R_w is the radius of the wheel.

Lateral slip angle for 3-axle vehicle

$$\alpha_{ij} = \tan^{-1}\left(\frac{v_y + l_i\dot{\psi}_z}{v_x}\right) - \delta \quad (10.1)$$

In equation (10.1), the steering angle, δ is only apply on $i = 1$ axle and the term $l_i\dot{\psi}_z$ is negative at $i = 2, 3$ positive at $i = 1$.

Longitudinal slip ratio model for 3-axle vehicle

$$V_{cti} = \sqrt{(v_y + l_i\dot{\psi}_z)^2 + (v_x + w_i\dot{\psi}_z)^2} \quad (11)$$

$$v_{Lxi} = V_{cti} \cos\alpha_{ij} \quad (12)$$

$$S_{a ij} = \frac{v_{Lxi} - \omega_{ij}R_w}{v_{Lxi}} \quad (13)$$

Note that, the term $l_2\dot{\psi}_z$ in equation (11) will be negative at $i = 2, 3$

Load transfer for 3-axle vehicle

$$F_{zijLT} = m_{0ij}g - m_s \frac{d_p}{l_1} a_x - m_s \frac{d_{rc}}{w} a_y - F_{zij} \quad (14)$$

F_{zijLT} is the load transfer on vehicle body wheel sides, m_{0ij} is the initial weight experience by the vehicle, d_{rc} is the distance from CG to roll axis, d_p is the distance from CG to pitch axis and F_{zij} is the vertical force on vehicle body wheel sides. In equation (14), the term $m_s \frac{d_p}{l_1} a_x$ is negative at $i = 1$ positive at $i = 2, 3$ and the term $m_s \frac{d_{rc}}{w} a_y$ is negative at $j = 1$ and positive at $j = 2$. Note that vehicle roll and pitch motion due to handling is similar with 2-axle vehicle (Muniandy *et. al.*, 2015; Darus & Yahaya, 2009; Uil *et. al.*, 2007).

2.3 Magic Formula

The latest Pacejka tyre model is PAC2002 (Adams, 2024; Hans, 2012) and is used in this paper. However, simplification is possible due to some insignificant factors included in the model. For example, like tyre pressure, effective rolling radius, rolling resistance moment and overturning moment. Moreover, Enviro 500 camber angle is 0.

3.0 PARAMETERS

Basic parameters of Enviro 500 Double-decker Bus can be found in the catalogue as shown in Table 1 (Abu, 2014; Prochowski & Zielonka, 2014; Slade, 2009; Belrzaeg *et. al.*, 2021).

As for PAC2002 parameters for 315/80 R22.5 tyres are obtainable from Adams tyre library files. Overall simulation model built in MATLAB Simulink software is shown in Figure 4.

Table 1: Enviro 500 parameters

Parameter	Value	Parameter	Value	Parameter	Value
l_{1CG}	4.7151 m	m_{031}, m_{032}	5000 kg	K_r	99195.9348 $\frac{Nm}{rad}$
l_{2CG}	1.2779 m	m_{u1}	406.8 kg	C_r	80900 $\frac{Nm}{s rad}$
l_{3CG}	2.5779 m	m_{u2}	513.6 kg	k_{ARB1}	100730 $\frac{Nm}{rad}$
h_{ra}	0.648 m	I_{xx}	49000 m^2	k_{ARB2}	105400 $\frac{Nm}{rad}$
h_{c8x}	5.25 m	I_{yy}	411000 m^2	k_{ARB3}	108500 $\frac{Nm}{rad}$
h_{c8y}	0 m	I_{zz}	396000 m^2	$k_{s21}, k_{s22}, k_{s31}, k_{s32}$	452000 Nm
h_{c8z}	1.43 m	I_w	15.1070 m^2	C_{11}, C_{12}	38789.9 $\frac{Nm}{s}$
M	24000 kg	l_{a1}	0.4318 m	C_{21}, C_{22}	53026.4 $\frac{Nm}{s}$
M_s	21345.6 kg	l_{a2}	0.4826 m	C_{31}, C_{32}	10480.3 $\frac{Nm}{s}$
w	2.545 m	l_{a3}	0.5588 m	K_p	881700 $\frac{Nm}{rad}$
$m_{011}, m_{012}, m_{021}, m_{022}$	3750 kg	k_{s11}, k_{s12}	387000 Nm	C_p	888203.5 $\frac{Nm}{s rad}$

3.1 Inputs

The half bump test input is by giving dimension from Figure 5 to the model with different travel and delay time according to the speed.

In handling test, steering dynamics formula was constructed as the input graphs for the tests. Equations $\delta_0 = \frac{l}{R \cdot \dot{\psi}_z}$, $\delta_i = \frac{l}{R \cdot \dot{\psi}_z}$ and $\cot\delta = \frac{\cot\delta_0 + \cot\delta_0}{2}$ will be used (Harnoor *et. al.*, 2025). All the road specification is following the standard set in (Jabatan Kerja Raya, 1985; ISO 3888-1, ISO 3888-2) the

example results of 40 km/h tests input is shown below. Figures 6 and 7 show the input signals used for the simulation purpose in this research.

The input signals shown in Figures 6 and 7 are based on proper industrial standards.

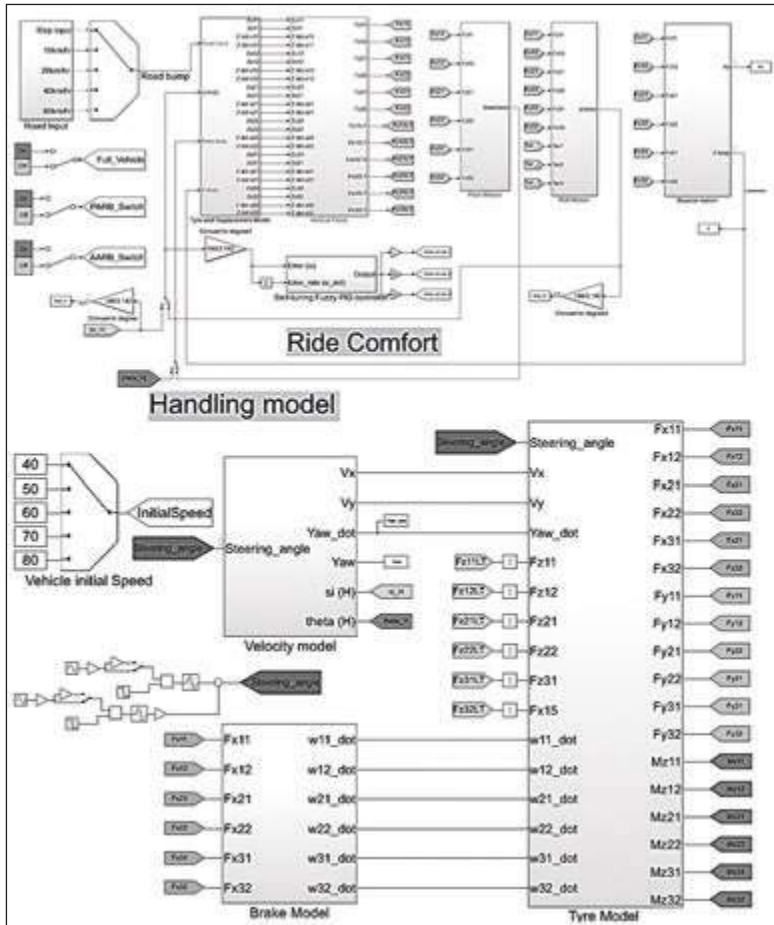


Figure 4: Overview of Full car, 3-axle vehicle mathematical model in Simulink

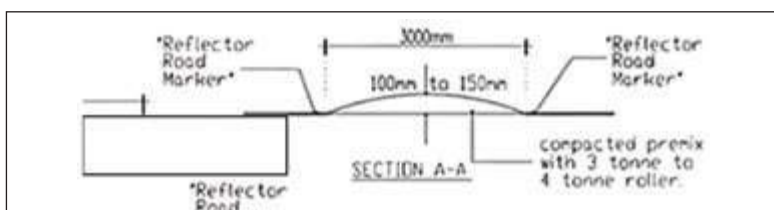


Figure 5: Specification of road bump (Jabatan Kerja Raya, 2015)

3.2 Controller

The chosen controller is self-tuning fuzzy PID controller, which has been tested in active suspension system before by various researchers. It is found that this controller is robust and suitable for high vibration applications. The self-tuning fuzzy PID controller structure is shown in Figure 8.

The diagram shown in Figure 8 is the actual Simulink model for the PID controller, with reference signal of constant zero fed into the controller. In this paper, it is found that $k_p = 300000$, $k_i = 17500$ and $k_d = 8500$ is best compared to other values. These values merely act like amplifiers to suit the required total force of A.ARB system. The active forces will then be distributed to each axle at 1:0.8:0.8 ratio. The Fuzzy logic memberships and rules studied from (Muniandy *et. al.*, 2015; Pivonka, 2002; Ross, 2010).

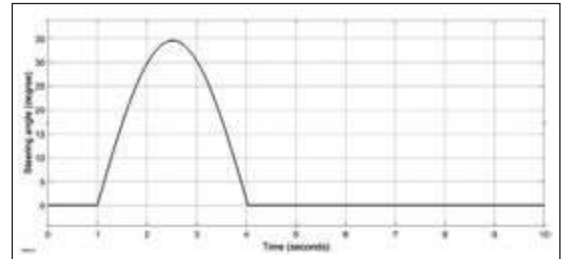


Figure 6: Steering input for U-turn test at 40km/h

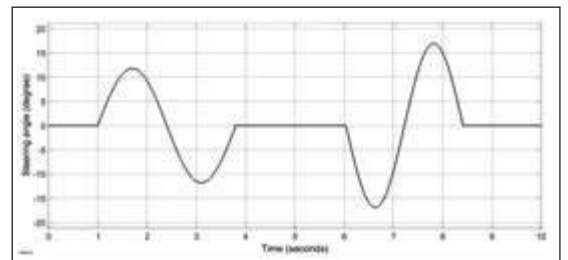


Figure 7: Steering input for ISO3888-1 test at 40km/h

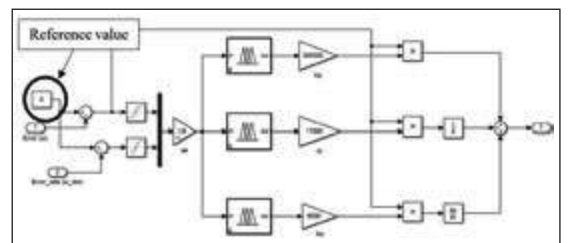


Figure 8: Roll angle result from half bump test at 40km/h

4.0 RESULTS AND DISCUSSION

4.1 Half Bump Test at 60km/h

Figures 9 to 12 show the results comparison for both passive and active anti-roll bar system for 40 km/h half bump test.

It can be seen from Figures 9 – 12, A.ARB system do have less excitation magnitude and quicker settling time compared to P.ARB. For example, in Figure 9, it can be seen the roll angle maintain within the margin of error of 0 degree, leaving the vehicle stay flat even after hitting the bump at 40km/h. Ride comfort has also been approved as evidence shown in Figure 12, as vertical acceleration is reduced by 22.05%. Further tests have been carried out to ensure the proposed controllers' robustness and repeatability.

4.2 U-turn (180-degree turn) test at 80km/h

Figures 13 to 15 show the results comparison for both passive and active anti-roll bar system for 80 km/h U-Turn test.

For handling tests, steering angle was used as input rather than road profile input as shown in previous half bump test. Again, similar to the half bump tests, Figures 13 – 15 also show that A.ARB system does have less excitation magnitude and quicker settling time compared to P.ARB.

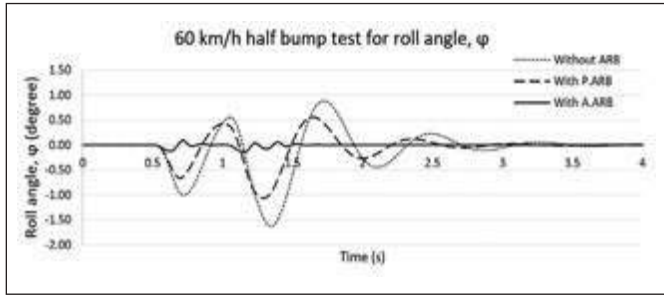


Figure 9: Roll angle result from half bump test at 40km/h

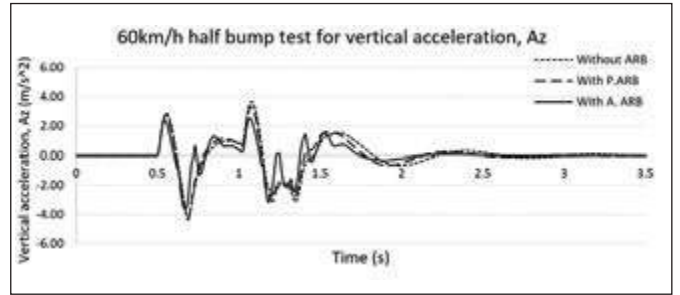


Figure 12: Vertical acceleration results from half bump test at 40km/h

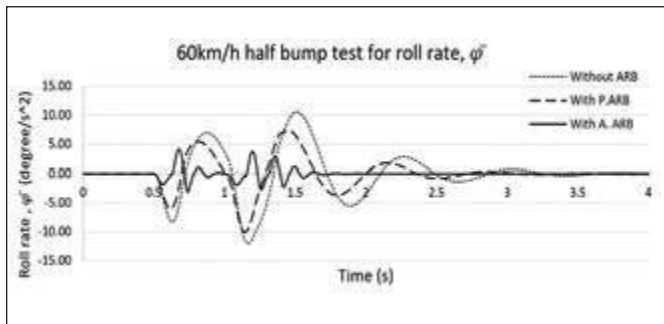


Figure 10: Roll rate result from half bump test at 40km/h

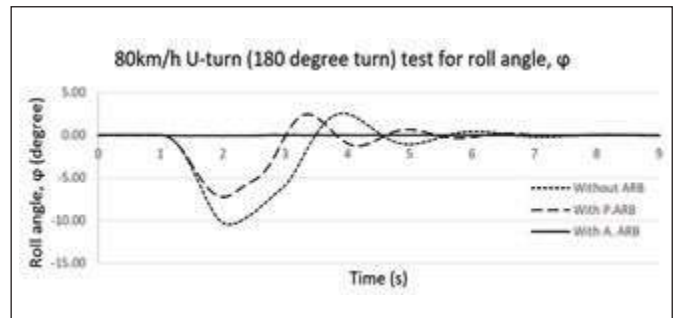


Figure 13: Roll angle result from 80km/h U-turn test

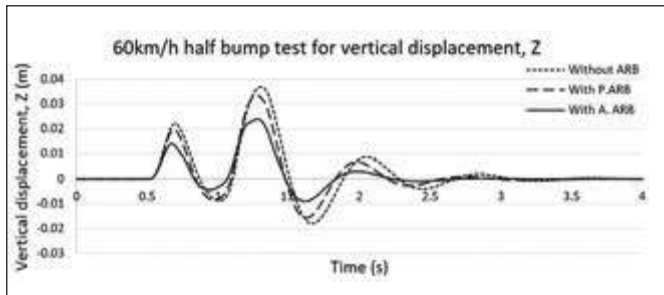


Figure 11: Vertical displacement result from half bump test at 40km/h

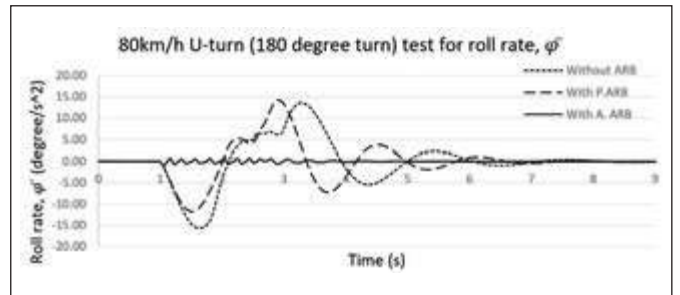


Figure 14: Roll rate result from 80km/h U-turn test

Table 2: RMS value comparison from half bump test at 40km/h

	Improvement of performance RMS comparison (%) between					
				Without ARB and		With P.ARB and
	Without ARB	With P.ARB	With A.ARB	With P.ARB	With A.ARB	With A.ARB
Roll angle	0.3617	0.2290	0.0219	36.68	93.93	90.42
Roll rate	3.0139	2.1169	0.6073	29.76	79.85	71.31
Z	0.0078	0.0068	0.0047	12.33	39.33	30.79
Az	0.7834	0.7558	0.5892	3.51	24.79	22.05

Table 3: RMS value comparison from U-turn test at 80km/h

	Improvement of performance RMS comparison (%) between					
				Without ARB and		With P.ARB and
	Without ARB	With P.ARB	With A.ARB	With P.ARB	With A.ARB	With A.ARB
Roll angle	4.1400	2.6505	0.0310	35.98	99.25	98.83
Roll rate	6.1502	5.1629	0.2337	16.05	96.20	95.47
Ay	1.7170	1.7700	1.5371	1.77	10.47	13.16

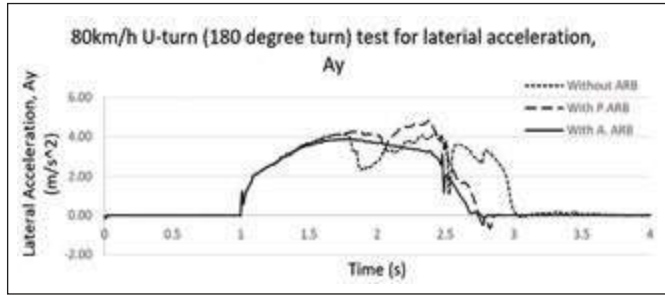


Figure 15: Lateral acceleration results from 80km/h U-turn test

4.3 Double lane change test (ISO 3888-1) at 80km/h

Figures 16 to 18 show the results comparison for both passive and active anti-roll bar system for 80 km/h double lane change test.

Figures 16 – 18 also shows similar trend in the differences of passive and active anti-roll bar performances.

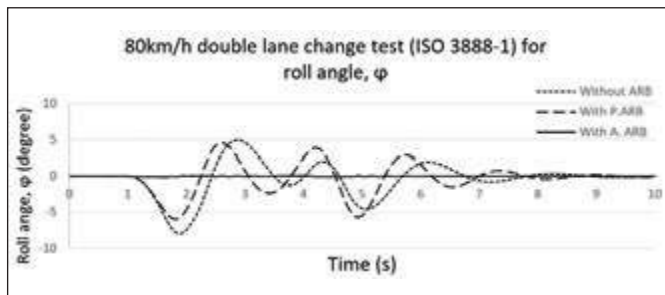


Figure 16: Roll angle result from 80km/h ISO 3888-1 test

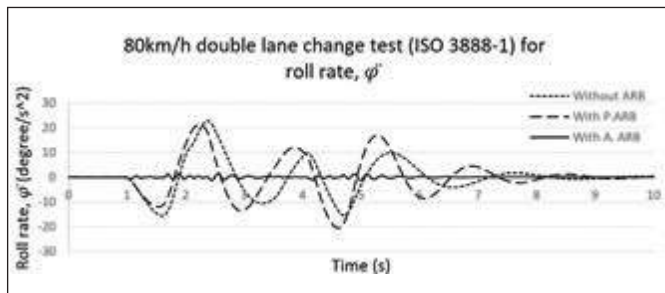


Figure 17: Roll rate result from 80km/h ISO 3888-1 test

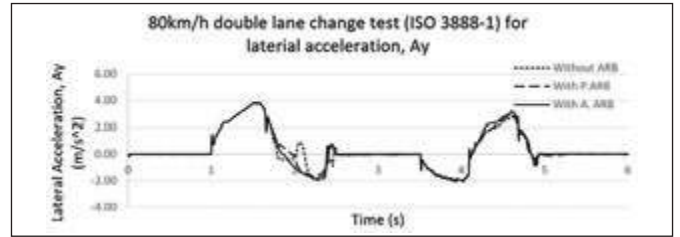


Figure 18: Lateral acceleration results from 80km/h ISO 3888-1 test

4.4 Handling moose test (ISO 3888-2) at 80km/h

Figures 19 to 21 show the results comparison for both passive and active anti-roll bar system for 80 km/h handling moose test.

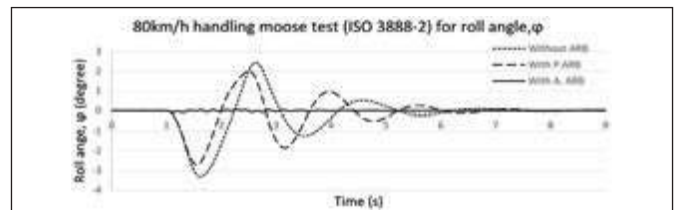


Figure 19: Roll angle result from 80km/h ISO 3888-2 test

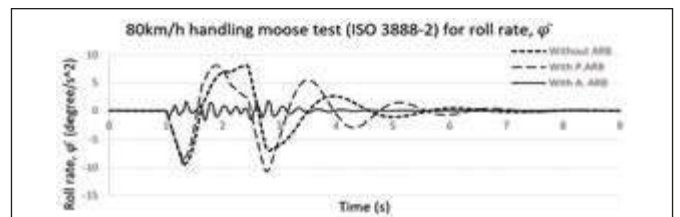


Figure 20: Roll rate result from 80km/h ISO 3888-2 test

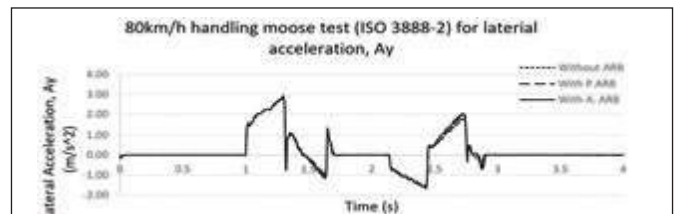


Figure 21: Lateral acceleration results from 80km/h ISO 3888-2 test

Table 4: RMS value comparison from ISO 3888-1 test at 80km/h

	Improvement of performance RMS comparison (%) between					
	Without ARB	With P.ARB	With A.ARB	Without ARB and		With P.ARB and
				With P.ARB	With A.ARB	With A.ARB
Roll angle	2.9618	2.6546	0.0319	10.37	98.92	98.80
Roll rate	8.6206	9.7639	0.4362	-13.26	94.94	95.53
Ay	1.2425	1.2608	1.3133	1.26	-5.69	-4.16

Table 5: RMS value comparison from ISO 3888-2 test at 80km/h

	Improvement of performance RMS comparison (%) between					
	Without ARB	With P.ARB	With A.ARB	Without ARB and		With P.ARB and
				With P.ARB	With A.ARB	With A.ARB
Roll angle	1.1068	0.9440	0.0208	14.72	98.12	97.80
Roll rate	3.4744	3.6139	0.4371	-4.02	87.42	87.90
Ay	0.6048	0.6135	0.6214	0.61	-2.74	-1.28

Lower vehicle speed of 40 km/h has been tested on ride tests, and 80 km/h has been tested for handling tests. It is found that the results of a higher speed test have a better percentage of reduction in roll motion and acceleration, hence ensuring the stability of the vehicle at high-speed maneuvers while keeping it comfortable. Since higher speed tests are more critical, those results are discussed in this paper.

4.5 Discussion

Overall, all the results do not exceed 5.886 m/s of lateral acceleration meaning that no tests have reached the rollover threshold. Moreover, A.ARB configuration performance is much better than P.ARB which the enviro 500 is using. By observing handling graph in Figure 9-21 although P.ARB has successfully obtained higher performance compared to without ARB configuration, the maximum amplitude of roll angle and roll rate are almost as high with a faster settling time from P.ARB. Some of the results show that P.ARB is not improving the performance rather it is worsening the performances as tested on ISO3888-1 and ISO3888-2. This is because ISO3888-1 involves a very aggressive steering input where P.ARB is having insignificant flexibility to react to the changes. On the other hand, A.ARB can maintain its performance because of the flexibility of the roll stiffness decided by the controller according to situations.

Other than that, the performance of bounce acceleration in the ride test and lateral acceleration in handling test, both the passive and active anti-roll bar failed to give significant improvement in handling tests. Although there is an improvement on bounce acceleration, on the other hand, performance of lateral acceleration is worsened by -4.16% on ISO3888-1 test and -1.28% on ISO3888-2. This is because the main function of the anti-roll bar is to reduce the roll and roll rate (Hamdi et. al., 2024). These will only directly affect vehicle's body roll. The downside is, this will cause the whole vehicle to be stiffer and rigid when A.ARB sensor detects the vehicle's body roll. Hence, causes the vehicle to experience more lateral acceleration. However, the lateral acceleration performance is worsened by only -2.22% through all tests. On the other hand, bounce acceleration can slightly improve by P.ARB due to the extra constant stiffness but as for A.ARB shows better performance is due to the active forces given by the controller.

5.0 CONCLUSION

A full car, 3-axle mathematical model consisting of 20DOF was successfully modeled and simulated within Matlab/Simulink environment. Throughout all results tested, it is proven that the active anti-roll bar was able to have up to an 86.93% improvement of comfort in roll rate on average, reducing roll angle up to 95.07% on average and 32.11% improvement of bounce comfort on average compared to P.ARB used in Enviro 500. Other than that, all handling tests have passed the rollover test by not reaching the rollover threshold in every test. On average, in every handling test, active anti-roll bar is able to reduce roll angle at least up to 98% and roll rate comfort has been improved up to at least 90% and successfully prevents it from reaching more than 96% compared to P.ARB.

Unfortunately, it is shown that active anti-roll bar must sacrifice some of the performance on lateral acceleration to obtain the improvement on roll rate and roll angle in handling test. However, the sacrifice is very low to negligible with an average of -2.22%. For future improvement, it is recommended to do it with an experimental approach. Experimental data will show better picture of the effectiveness of the proposed controllers, as the simulation in this study only include results with ideal flat plane road inputs. ■

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AUTHORS' CONTRIBUTIONS

Vijayapragas Muniandy	Conceptualisation, study design, and supervision.
Tze Peng Loo	Data collection, methodology, and formal analysis.
Jeyagopi Raman	Writing review, editing, and final manuscript approval.
Sudesh Nair Baskara	Writing review, editing, and final manuscript approval.

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PROFILES



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A CRITICAL REVIEW OF HOMOPOLAR GENERATORS: DESIGN, EFFICIENCY, MODELLING, AND PRACTICAL VIABILITY

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Abstract

This review critically examines the operating principles, design considerations, efficiency trade-offs, and modelling approaches of direct current machines that generate very high currents at low voltages. Starting with the theoretical background of electromagnetic induction, such as the Faraday paradox and Lorentz force, the review follows how conceptual arguments have been applied in engineering practice. The literature on rotor-stator designs, magnet approaches, and current-collection schemes is reviewed to demonstrate how efficiency, durability, and scalability are influenced by design trade-offs. Reported uses of HPGs in pulsed-power systems, welding, electromagnetic launchers, and fusion experiments illustrate recurring problems, including low terminal voltage, resistive heating, and brush wear. Advances in computational modelling and materials have enhanced performance predictions, but long-term experimental validation is lacking. Across the literature, consensus and future research directions emphasise the need for scalable, manufacturable HPG designs integrating advanced materials, improved contact technologies, and design-for-manufacturing principles. Future research should integrate advanced materials, improved contact technologies, and design-for-manufacturing principles to fully realise the potential of homopolar generators.

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Homopolar generator, Electromagnetic induction, Engineering design advances, High-current applications, Technological limitations

1.0 INTRODUCTION

1.1 Background of the Study

Early generators of electricity transformed alternating current (AC) into direct current (DC) utilising mechanical commutators that wore out and had to be serviced often. To address these disadvantages, the homopolar generator (HPG), or Faraday disc, came into use in early 19th century by Michael Faraday. It proved that a conductor in rotation immersed in a magnetic field can generate DC directly without mechanical commutation (Paulus, 2018).

An HPG is a revolving conductive disc or cylinder in a constant magnetic field, producing a stable DC output via electromagnetic induction. Since it does not have commutators, the system reduces mechanical wear and provides consistent operation on high-current loads (Engel & Kontras, 2020). Basically, an HPG directly translates mechanical rotation into electric potential between the disc's rim and centre and generates continuous DC with straightforward mechanics (Paulus, 2018).

1.2 Significance of the Study

Homopolar generators are still applicable in pulsed-power systems, electromagnetic launchers, and high-current industrial use due to their capability for delivering very high current at low voltage. Recent advances in materials, cooling, and computational design have revitalised interest in HPGs as compact, efficient sources for specialised industrial and military applications. Their mechanical strength, simplicity, and lack of commutating parts minimise maintenance and downtime over traditional DC machines. Possible applications are also envisioned in hybrid propulsion and clean-energy applications, although practical implementation remains limited.

This review synthesises past and recent literature on HPGs, analysing theoretical principles, design development, and technological innovations solving long-standing constraints. It also shows current challenges and gaps that limit broader adoption.

1.3 Scope and Limitations

The review covers the design, performance, and applications of HPGs from early development to recent advances. It focuses on materials, rotor-stator geometry, brush technologies, and computational modelling. Restrictions include reliance on literature available, exclusion of classified military designs, and the lack of long-term performance data or industrial-scale results.

1.4 Objectives of the Literature Review

1. Examine the theoretical principles of homopolar generators to explain the principles on which they operate.
2. Survey historical and recent engineering advances in HPG design, including construction options, material uses, and performance solutions.
3. Assess documented uses of HPGs in scientific, industrial and military applications.
4. Identify common challenges and limitations that have restricted the wider use of HPGs.
5. Highlight areas of research gaps and future research directions to inform future research and possible technological innovations.

2.0 METHODOLOGY

In this research, a systematic literature review method has been used to examine the present research situation on homopolar generators. The research procedure entailed the following steps:

- Literature Search:** Authoritative web sources, peer-reviewed journal articles, doctoral dissertations, conference papers, technical reports, patents, and other databases were searched including IEEE Xplore and Google Scholar. Some keywords were homopolar generator, Faraday disc, unipolar generator, Lorentz force, electromagnetic induction, and scalar-vector potential.
- Selection Criteria:** Studies were chosen based on relevance, and technical rigor. Priority was put on the works that covered design improvement, efficiency, material development, theoretical modelling or experimental validation of homopolar generators.
- Data Extraction:** Relevant information was extracted on design trends, technological limitations, theoretical frameworks, and practical applications. It focused on the gaps in the literature that could be used in the future research directions.
- Analysis and Synthesis:** The literature obtained was analysed to determine the recurring trends, important findings, and unresolved problems. A comparative analysis has been done to point out differences between theoretical explanations (Faraday, Lorentz, and scalar vector approaches) and practical applications of homopolar generators.

2.1 Theoretical Foundations

2.1.1 Lorentz Force Vs Faraday's Law

Figure 1 illustrates the classical scenario described by Faraday's Law of Electromagnetic Induction. This law states that an electromotive force (EMF) is generated in a closed circuit as the magnetic flux through the circuit varies with time. This theory has been very effective in explaining the behaviour of most electromagnetic systems; however, in the case of homopolar generators such as the Faraday disc, further theoretical and experimental work shows that the standard form of Faraday's law cannot by itself fully account for the observed behaviour (Baumgärtel & Maher, 2022).

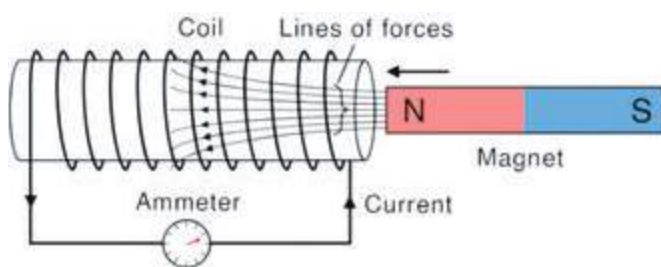


Figure 1: Faraday's Law

However, further theoretical and experimental studies have shown that the standard form of Faraday's Law, when applied at the circuit level, cannot by itself fully explain the operation of a homopolar generator. According to Faraday's law,

$$E = -\frac{d\Phi B}{dt}$$

an EMF should only arise when the magnetic flux is, that is, the total magnetic field passing through a circuit — changes with time. In a homopolar generator, the **magnetic field** is

static, and the **geometry of the system** remains unchanged during operation. This leads to what has historically been called the **Faraday Paradox** — a situation in which a measurable EMF and steady current are produced even though there is no apparent time-varying magnetic flux (Srinivasa, 2015).

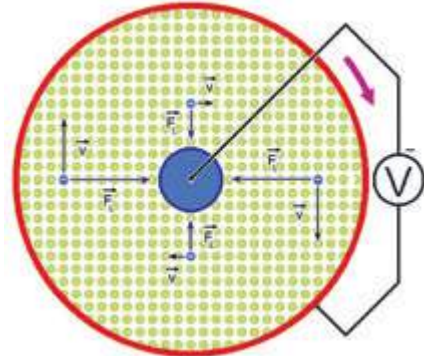


Figure 2: Working principle of a homopolar generator: due to Lorentz force FLF_{LFL} , negative charges are driven towards the centre of the rotating disc, creating a voltage between centre and rim (reproduced from Wikipedia, 2021)

In contrast, the Lorentz Force Law offers a more direct and physically accurate explanation. Figure 2 demonstrates the working principle of a homopolar generator due to Lorentz force. The Lorentz force,

$$F' = q(\mathbf{v}' \times \mathbf{B}')$$

describes how a moving charge q experiences a force in a magnetic field. For a rotating conducting disc in an axial magnetic field \mathbf{B} , electrons at a radius r move with tangential velocity $\mathbf{v} = \boldsymbol{\omega} \times \mathbf{r}$, producing a radial electric field

$$E_r = \boldsymbol{\omega} r \mathbf{B}$$

Integrating this field from the centre to the rim yields the open-circuit EMF:

$$E = \frac{1}{2} B \omega R^2$$

where R is the disk radius and ω its angular velocity. This formulation accurately predicts the observed potential difference in homopolar generators, confirming that EMF can arise from charge motion within a static magnetic field, even when total magnetic flux remains constant (Gobbi, 2024). This view is consistent with experimental findings and describes the mechanism by which homopolar generators can generate direct current (DC) even though there is no time varying flux. Thus, while Faraday's Law provides the macroscopic view of induction, the Lorentz Force Law explains the microscopic mechanism responsible for EMF generation in unipolar systems. Both are consistent within Maxwell's equations, but the Lorentz force interpretation explicitly captures the role of moving conductors and free charges in steady magnetic fields.

2.1.2 Scalar-Vector Explanation of Induction

Although the Lorentz force law successfully explains most behaviours of homopolar generators, certain experimental configurations still defy complete description by either Faraday's law or the Lorentz framework alone. These include cases where induced voltages occur without relative motion

between conductors and magnetic fields or without apparent flux change.

To address these anomalies, Mende (2018) introduced the scalar–vector potential model, which extends classical electrodynamics by incorporating relativistic effects into the electromagnetic potentials. In this model, the scalar potential of a moving charge depends on its relative velocity, linking the scalar and vector potentials through a unified relativistic framework. Mende argues that in classical formulations, Maxwell’s equations and the Lorentz force are often treated as separate components of electrodynamics.

The scalar–vector potential approach attempts to unify them by expressing induction as a combined effect of potential variations in both time and space. This formulation can theoretically account for induction phenomena in which neither a changing magnetic flux nor charge motion in a magnetic field (as described by Lorentz) is sufficient to explain the observed EMF.

Although still non-mainstream, the scalar–vector potential model provides an expanded theoretical lens for understanding unipolar induction and resolving long-standing paradoxes that arise when applying Faraday’s and Lorentz’s laws independently.

2.2 Engineering Designs and Considerations

2.2.1 Construction and Functional Design

2.2.1.1 Rotor & Stator Design

Figure 3 and Figure 4 illustrate how rotor mass and conductor length govern homopolar generator (HPG) performance. Lighter rotors accelerate quickly and reach peak efficiency sooner—suited for pulsed or short-burst applications—while heavier rotors store more kinetic energy and provide steadier current for continuous duty (Engel & Kontras, 2020). Efficiency improves with reduced conductor length (difference between inner and outer radii) and optimised field-winding placement. Positioning the winding on the stator simplifies cooling and allows a slotless configuration that minimises rotor losses (Liu, Yu, & Xie, 2023). Rotor geometry and stator structure therefore jointly determine machine efficiency and robustness.

Early studies demonstrated the feasibility of large pulsed-power HPGs but lacked computational tools for optimisation. Later works, such as Engel & Kontras (2020), addressed this limitation using PSICE modelling to predict efficiency trends and mechanical stress behaviour, marking a shift from purely experimental toward simulation-guided design.

2.2.1.2 Magnetic and Contact Systems

Magnet and brush assemblies define both excitation control and current-collection quality. Permanent magnets (ferrite or neodymium) provide compact, maintenance-free operation but are limited to $\approx 1.2\text{--}1.4\text{ T}$ (Engel & Kontras, 2020; Prakht *et al.*, 2023). Electromagnets enable adjustable fields and voltage regulation but require cooling and auxiliary power (Köster & Binder, 2022). Superconducting coils achieve higher flux density and lower loss at the expense of cryogenic complexity (Füger *et al.*, 2016).

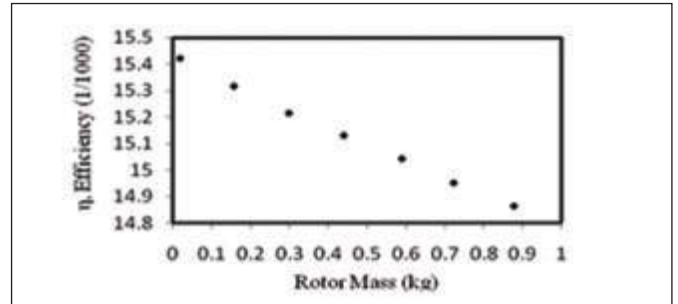


Figure 3: Effect of rotor mass on efficiency as predicted by the PSICE model. Reproduced from *Analysis and Design of Homopolar Motors and Generators* (Figure 13), by Engel and Kontras (2020)

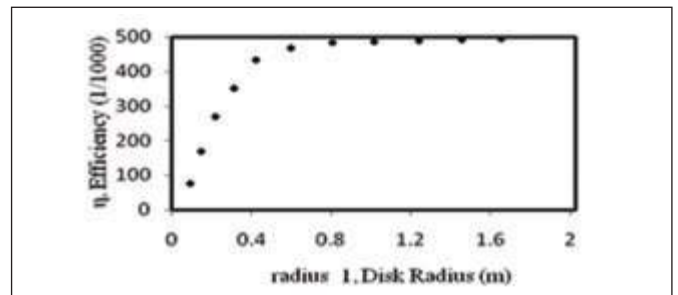


Figure 4: Effect of conductor length (inner–outer disc radii difference) on efficiency as predicted by the PSICE model. From *Analysis and Design of Homopolar Motors and Generators* (Figure 14), by Engel and Kontras (2020)

Current collection uses graphite, liquid-metal, or hybrid brushes. Graphite brushes are inexpensive and self-lubricating but can deteriorate rapidly under high currents (Li *et al.*, 2024). Liquid-metal contacts reduce voltage drop but pose sealing and safety challenges (Avalos-Zúñiga *et al.*, 2017). More recent work on advanced surface coatings (e.g., copper – graphene composite coatings) has shown significant improvements in current-carrying friction characteristics and corrosion resistance at high current densities (Zhao *et al.*, 2025). Choosing magnet and brush systems thus balances controllability, efficiency, and maintenance demands.

While traditional HPGs relied on bulky electromagnets for excitation, recent research by Prakht *et al.* (2023) integrates ferrite magnets with auxiliary windings to reduce losses and improve controllability. This hybrid approach exemplifies how modern designs extend the earlier focus on flux strength toward efficiency and dynamic regulation.

2.2.2 Design Configurations in Literature

2.2.2.1 Disc Vs Drum Type

Disc-type homopolar generators, such as the original Faraday wheel, as illustrated in Figure 5, are mechanically simple and easy to analyse. They consist of a solid conductive disc with central and rim brushes. Avalos-Zuñiga *et al.* (2023) experimented with a Bullard-type disc (radius 30 cm, thickness 3 cm) at 7 Hz, creating $\sim 40\text{ mT}$ central magnetic field with radial voltage drop measurable. Such configurations are perfectly suitable for instruction, small-scale experimentation,

and simulation-based optimisation (COMSOL Blog, 2018). Disc-type generator has thus become a desirable option in lower-power and laboratory-scale applications where ease of assembly, cost-effectiveness and ease of access to analysis are of concern. These machines employ a cylindrical rotor, typically so as to have as high surface area and speed and as low mechanical wear as possible.

Drum-type homopolar machines, as depicted in Figure 6, employ a cylindrical (or drum) rotor structure rather than a flat disc, thereby increasing the active surface area and enabling better structural integrity under high rotational stress. Such machines have been noted for their high durability and capability to handle large bursts of current and rapid energy transfer (Bianchini *et al.*, 2011). The drum-type rotor typically drives current along the cylinder length and is therefore well suited for applications demanding high energy throughput, pulsed-power defence systems, plasma experiments, or energy storage bursts.

Though direct comparison is restricted, disc types perform best in low-energy, uncomplicated applications and drum types offer mechanical strength and high-speed energy storage, with preference to high-power pulsed operation. This distinction is summarised in Table 1.

2.2.2.2 Rotation Configurations

The behaviour of electromotive force (EMF) generation in homopolar generators depends critically on which component is rotating. In one common configuration, a conductive disc rotates in a nearly uniform magnetic field created by a magnet with large pole pieces. As the disc moves through the static field, Lorentz forces drive charge separation and an EMF is induced; conversely, simply rotating the magnet alone does not produce a steady EMF, which confirms that conductor motion relative to the field is essential (van Hees, 2014). This principle underlies the design of various rotational configurations of HPGs.

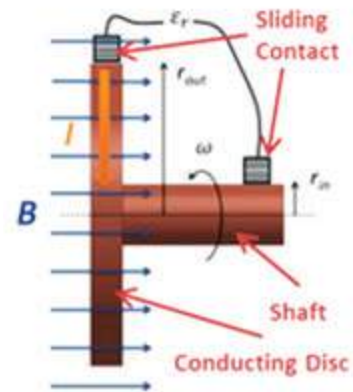


Figure 5: A simple sketch of a disc-type homopolar machine indicating the basic machine parameters. Reproduced from Füger, R., Matsekh, A., Kells, J., Sercombe, D. B. T., & Guina, A. (2016). A superconducting homopolar motor and generator, new approaches

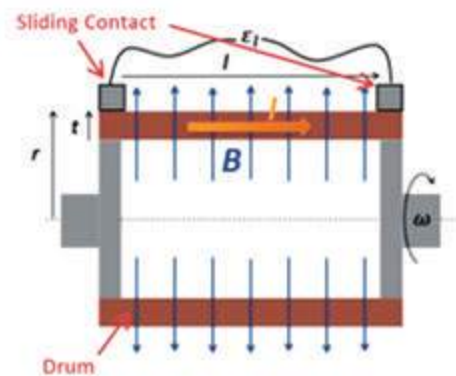


Figure 6: A sketch of a drum-type homopolar machine indicating the basic machine parameters. Reproduced from Füger, R., Matsekh, A., Kells, J., Sercombe, D. B. T., & Guina, A. (2016). A superconducting homopolar motor and generator—new approaches

Table 1: Comparison of Disc-Type and Drum-Type Homopolar Generators

Feature	Disc-Type HPG	Drum-Type HPG
Geometry	Flat conductive disc with brushes at rim and hub	Cylindrical drum rotor; can be thin-walled; rotor mass and geometry optimised for high-speed pulsed operation (Bianchini <i>et al.</i> , 2011)
Simplicity	Very simple design; easy to build and simulate	Mechanically more complex; requires precise balancing, supports, and robust bearings
Experimental Data	Copper disc (30 cm radius, 3 cm thick) at ≈ 7 Hz produced ~ 40 mT central field and measurable radial voltage (Avalos-Zúñiga <i>et al.</i> , 2023)	produced ~ 40 mT central field and measurable radial voltage (Avalos Zúñiga <i>et al.</i> , 2017) Cylindrical rotor with drum type configuration demonstrated high-speed pulsed operation, capable of kiloampere-range currents and rapid energy bursts (Bianchini <i>et al.</i> , 2011)
Voltage Output	Typically low (few volts at lab scale)	Moderate (tens to ~ 150 V), scalable with rotor size and speed
Current Capability	Limited (≤ 100 A in small-scale setups)	Very high (kiloampere range)
Applications	Educational demonstrations, simulation studies, validation of models	Pulsed power, plasma research, defense/military energy systems
Advantages	Low cost, accessible, excellent for teaching and proof-of-concept studies	High durability, large energy throughput, better structural integrity
Limitations	Severe brush losses at hub, poor scalability to high power	More expensive, mechanically complex, requires advanced contact systems

2.2.3 Materials and Thermal Management

Material selection controls efficiency, thermal stability, and manufacturability. Ferrite magnets provide low cost and temperature resilience but weak flux; rare-earth types (Nd-Fe-B) generate stronger fields and torque at the cost of active cooling (Prakht *et al.*, 2023). Hybrid ferrite–electromagnetic excitation minimises torque ripple and improves controllability (Prakht *et al.*, 2023). Superconducting HPGs (Figure 7) achieve near-zero resistance and ripple-free DC output but add cryogenic complexity and mechanical stress (Füger *et al.*, 2016). Designers must balance flux density, stability, and cost to match target applications.

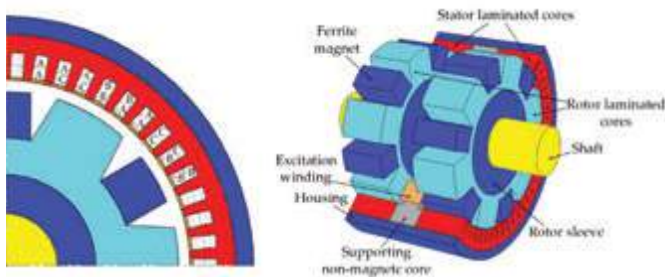


Figure 7: SHG approximate geometry: (a) Cross-section of the stator and armature winding; (b) General view of the rotor. Reproduced from Prakht, Dmitrievskii, & Kazakbaev (2023)

Thermal and durability issues remain critical. High currents and mechanical stress accelerate wear in liquid metal contacts (Avalos Zúñiga, Priede, & Bello Morales, 2017). Ferrite magnets mitigate eddy current heating, while rare earth and superconducting systems demand robust cooling. Proper thermal design ensures longevity and operational reliability under sustained high current loading.

Foundational studies established the unipolar induction principle (Baumgärtel, 2022); yet new investigations like Wang *et al.* (2024) and Füger *et al.* (2016) adapt it to superconducting systems, achieving near zero resistance and higher power density. The transition from copper to superconducting materials underscores the field's shift from proof of concept toward high performance implementation.

2.3 Applications

Homopolar generators (HPGs) find a range of uses in high-power pulse systems and take advantage of the fact that they can generate high current pulses by directly converting the rotational inertia of a mechanical rotor into electrical energy.

Welding. Pulsed-power HPGs can weld carbon and stainless steel with greater energy efficiency than traditional arc welding (The Fabricator, 2019; Figure 8).

Defense and Research. In research and defense contexts, HPGs have been proposed as sources of high current pulses for electromagnetic launch systems and as kinetic energy storage devices in pulsed power applications (Golea, 2021).

Educational Use. HPGs are perfect for the pedagogy of concepts such as the Lorentz force and DC generation because of simplicity and visual intuition. Industrial or defense systems use the same concepts in low-voltage, low-power experiments.

Energy-Dense Applications. Homopolar generators (HPGs) are particularly suited to applications involving high levels of electrical energy delivered in a short time. By converting rotational kinetic energy into high current pulses, they are useful in situations where conventional energy storage is constrained by size, weight, or response time. Recent work on superconducting homopolar machines indicates that HPG architectures are increasingly capable of very high power density and rapid energy transfer in compact form factors (Kalsi *et al.*, 2019).

Energy Storage. HPGs are appropriate for short-duration, high-power bursts, being superior to chemical batteries in situations requiring instantaneous megawatt-class power with fewer thermal and degradation constraints (Kalsi *et al.*, 2019).

Limitations. Low terminal voltage requires series connections or step-up converters, complicating the system. Mechanical storage is wear-prone and subject to durability concerns under repeated cycling. Such issues render HPGs most competitive in niche, high-energy, short-duration applications instead of continuous-duty systems.



Figure 8: Experimental homopolar generator used in pulsed-welding applications. Reproduced from The potential of homopolar-generator welding (The Fabricator, 2019)

2.4 Technological Limits and Trade-Offs

2.4.1 Reported Challenges: High Resistive Losses, Low Voltage Output, Brush Contact Resistance

Homopolar generators (HPGs) continue to present design challenges related to resistive losses and system voltage levels. Recent work on synchronous homopolar machines demonstrates that optimising stator excitation and rotor design can significantly reduce losses, though traditional concerns of low-voltage output (due to the single conductive path) and contact/brush systems still warrant attention (see Section 2.2.1.2; Prakht, Dmitrievskii, & Kazakbaev, 2023).

Brush and collector systems continue to pose reliability challenges in homopolar generators (HPGs). Liquid-metal contacts such as NaK and gallium alloys can carry very high currents with reduced voltage drop but suffer from sealing, magnetohydrodynamic flow, and corrosion issues (Ma *et al.*, 2023). Arcing and mechanical wear limit graphite and other solid brushes., while newer foil and fiber-contact systems show potential for improving stability but are not yet optimised

Table 2: Comparison of Losses in Traditional vs. Homopolar Generators

Loss Type	Traditional Generator	Homopolar Generator
Mechanical	Present (bearing friction, windage)	Present (bearings, brushes, rotor drag)
Core	Significant (hysteresis and eddy currents in laminated core)	Negligible (steady, unidirectional flux)
Copper (I^2R)	Present in stator and rotor windings	Present in conducting disc and brushes (dominant)
Stray load	Present (slot harmonics, flux pulsation)	Negligible (no slots, smooth disc, constant flux)

for long-duration high-current operation. Moreover, graphite brushes are inexpensive and self-lubricating but can deteriorate rapidly under high currents (Li *et al.*, 2024). Liquid-metal contacts reduce voltage drop but pose sealing and safety challenges (Avalos-Zúñiga *et al.*, 2017).

Although conventional generators experience various types of losses, Table 2 shows that some of these losses are insignificant in HPGs due to their special design and constant magnetic flux (see also Section 2.5.1 for performance modelling discussion).

Brush and collector contacts remain a significant challenge in homopolar generators (HPGs). Graphite brushes often suffer from arcing, elevated temperature, and accelerated wear due to poor contact conditions, especially under high currents and low contact pressure (Li, Zhang, & Chen, 2024). Liquid-metal contacts (e.g., NaK alloys) may offer lower resistance pathways but introduce demands on containment, corrosion control, and system complexity. Advances in multi-contact foil, fiber and hybrid brush systems aim to enhance contact stability and reduce resistance; however, contact assemblies still impose meaningful losses and operational limitations in HPG systems.

2.4.2 Economic Considerations

Beyond the technical issues described above, economic factors play a crucial role in assessing the viability of homopolar generators (HPGs). For instance, one recent market report indicates an average unit cost of approximately USD 37,000 for an HPG system in 2023 (QY Research, 2025). This capital cost becomes more significant when combined with recurring maintenance expenses associated with high-current contacts, brush wear, and resistive losses (see Section 2.4.1). Although HPGs are often cited for their suitability in short-duration, high-current pulses, their relative inefficiency in longer-term continuous operation raises concerns about lifecycle cost and return on investment.

Therefore, material choices such as high-purity copper, permanent or superconducting magnets, and advanced contact assemblies must be evaluated not only for performance but also for cost-effectiveness and manufacturability (see Section 2.4.3.1). Future research should incorporate detailed cost-benefit analyses and total-cost-of-ownership studies to guide design trade-offs and deployment decisions.

2.4.3 Technological Advancements

2.4.3.1 High-Temperature Superconducting Magnets and Conduction Cooling

Advances in high-temperature superconducting (HTS) technology have enabled homopolar machine designs with markedly improved flux density and reduced resistive losses.

For example, the use of HTS field coils in a homopolar synchronous machine has shown promise for enhanced performance and higher current density in pulsed power applications (Hwang, 2021). Though cryogenic complexity and cost remain obstacles, HTS magnets enable ripple-free, high-efficiency performance suitable for advanced pulsed-power systems (Füger *et al.*, 2016).

2.4.3.2 Designs Suggested to Improve Output or Scalability

Emerging homopolar generator (HPG) designs focus on improving output voltage and machine scalability. For example, a recent design patent describes a drum-wound, air core HPG with radial flux focusing aimed at improving voltage output and current capability by optimising magnetic circuit geometry (Mandes, 2014). Although researchers have yet to fully validate these architectures experimentally, such architectures indicate promising paths toward modular, scalable HPGs suitable for high current, pulsed power applications.

2.5 Performance Modelling and Structural Consideration

2.5.1 Efficiency Improvements

Current modelling research has been aimed at enhancing HPG efficiency by fine-tuning slot geometry, excitation arrangement, and magnetic configuration. Prakht, Dmitrievskii, and Kazakbaev (2023) showed how incorporating ferrite magnets for synchronous HPG rotors improves stator usage and minimises machine size.

To efficiently model this intricate 3D structure, the authors used a reduced 2D FEM model along with Nelder-Mead optimisation, conserving computation time while not losing accuracy. Results indicated clear gains: structural adjustments such as increased stator slot area and reduced air gap reduced average generator losses and peak armature current (Figure 9, Figure 10, Figure 11, Figure 12, and Figure 13).

Quantitative results confirm these improvements. According to Table 3, efficiency at 750 rpm increased from 78.0% to 84.4%, while average losses decreased by about 16.9%. The maximum armature current at rated torque was reduced by nearly 27%, lowering copper losses. When comparing SHGs with and without ferrite magnets, Table 4 showed that efficiency improved from 90.4% to 92.7% at high speed (3450 rpm), demonstrating that hybrid excitation is more effective than conventional brushless designs without magnets (Prakht *et al.*, 2023).

Overall, hybrid magnets, bipolar topologies, and FEM-optimised designs have boosted HPG efficiency, rendering contemporary systems appropriate for high-end pulsed-power and transport requirements like railway auxiliary power units.

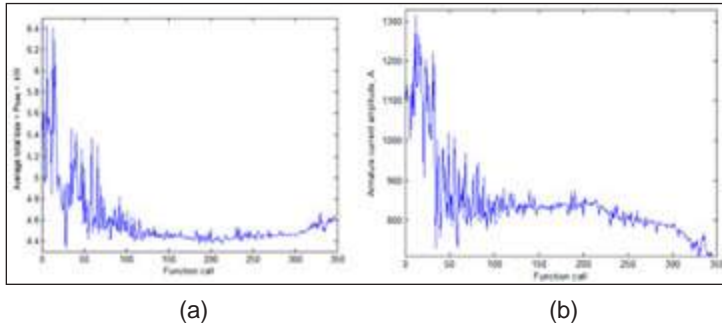


Figure 9: Change of generator parameters during optimisation: (a) Average losses; (b) Maximum armature current. Reproduced from Prakht & Dmitrievskii (2023)

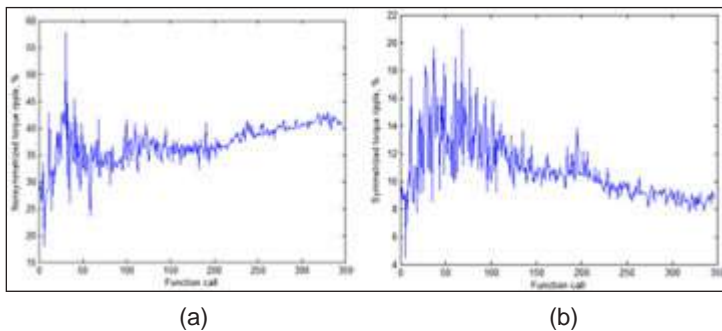


Figure 10: Torque ripple changes during optimisation: (a) Nonsymmetrised; (b) Symmetrised output. Reproduced from Prakht & Dmitrievskii (2023)

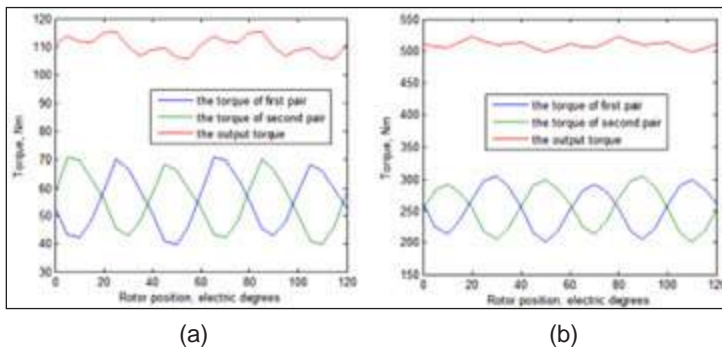


Figure 11: The torque ripple of the individual SRSC and the symmetrised (output) torque ripple after optimisation: (a) at 3450 rpm; (b) at 75. Reproduced from Prakht and Dmitrievskii (2023), *Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars*

2.6 Critiques and Gaps in the Literature

2.6.1 Experimental Weaknesses

Experimental work on homopolar generators (HPGs) remains constrained by short test durations, contact system instability, and losses arising from high speed rotor conditions. In one recent experiment, leakage of liquid metal contacts at elevated rotation rates led to voltage fluctuations and limited continuous operation of a homopolar disc dynamo (Avalos Zúñiga, Priede, & Bello Morales, 2017).

More broadly, studies of current transfer mechanisms in homopolar machines highlight sliding or liquid metal contacts as sources of high loss and maintenance burden (Masson, 2024).

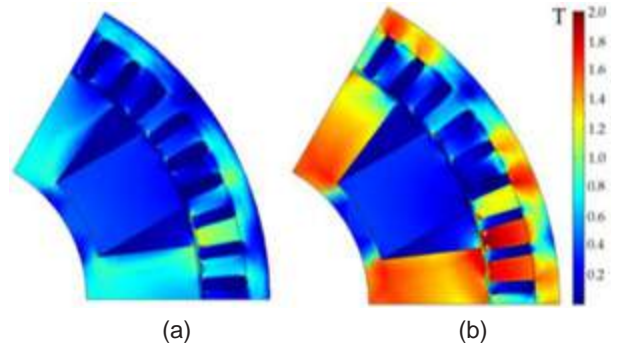


Figure 12: Pole-sector geometry of the generator for the initial design: (a) Maximum speed; (b) Maximum torque. Reproduced from Prakht and Dmitrievskii (2023), *Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars*

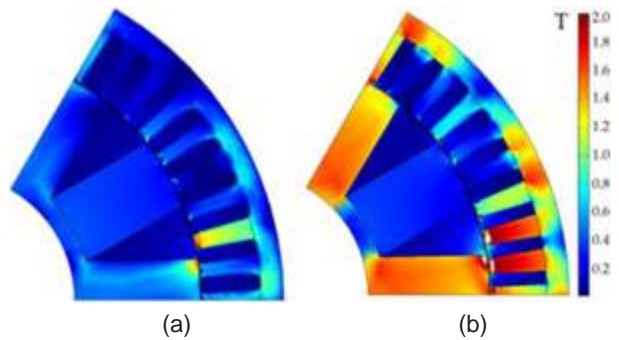


Figure 13: Pole-sector geometry of the generator for the optimised design: (a) Maximum speed; (b) Maximum torque. Reproduced from Prakht and Dmitrievskii (2023), *Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars*

Furthermore, experimental theoretical analysis of contemporary unipolar machines reveals that measurable losses and deviations from model predictions remain significant, indicating that practical HPG systems have yet to realise their full theoretical performance potential (Patrinos, 2024).

A number of experimental studies on homopolar generators point out various limitations that influence reliability and generalisability of findings. Table 5 summarises the reported weaknesses in the selected studies.

These weaknesses indicate that although experimental data can provide insights into component-level performance, broader validation of homopolar generators remains limited by methodological and operational constraints. Factors such as contact-system instability, high-speed rotor losses, liquid metal leakage, and divergence from theoretical models restrict long-term and high-power evaluation. Consequently, while laboratory tests inform design and optimisation, the full practical potential of HPGs has yet to be realised (Avalos Zúñiga, Priede, & Bello Morales, 2017; Masson, 2024; Patrinos, 2024).

Table 3: Generator characteristics before and after optimisation. Reproduced from Prakht and Dmitrievskii (2023), Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars

Characteristics	Initial Design 1	Initial Design 2	Optimised Design 1	Optimised Design 2
Loading case, i	1	2	1	2
Rotational speed, n (rpm)	3450	750	3450	750
Armature phase current amplitude, I_{arm} (A)	408	1035	375	700
Efficiency, %	94.5	78.0	92.7	84.4
Mechanical power on the generator shaft, P_{mech} (kW)	40	40	40	40
Shaft torque, N·m	111	510	111	510
Output electrical power, P_I (kW)	37.97	32.36	37.22	34.90
Armature DC copper loss, $P_{arm DC}$ (kW)	1.12	7.21	1.29	4.51
Armature eddy-current copper loss, $P_{arm AC}$ (W)	123	46	402	157
Stator laminated steel loss, $P_{iron st}$ (W)	756	379	960	411
Rotor laminated steel loss, $P_{iron rt}$ (W)	33	9	121	24
Excitation copper loss, P_{ex} (W)	187	1170	151	1123
Total loss, P_{loss} (kW)	2.22	8.81	2.93	6.22
Average losses, (P_{loss}) (kW)	5.51	-	4.58	-
Turns number in the armature slot	4.41	-	6.82	-
Required rectifier power (kW)	104.0	-	70.3	-
Power factor	0.926	0.804	0.989	0.854
Line-to-line voltage amplitude, V_{arm} (V)	116.0	44.9	116.0	67.4
Nonsymmetrised torque ripple, %	35	28	56	41
Symmetrised torque ripple, %	9.8	4.3	8.6	4.5
Flux density in the non-laminated parts of the magnetic core, T	0.4	1.3	0.1	1.5

Table 4: Characteristics of generators without magnets and with ferrite magnets. Reproduced from Prakht and Dmitrievskii (2023), Optimal Design of Synchronous Homopolar Generator with Ferrite Magnets for Railway Passenger Cars

Characteristics	SHG without Magnets (i=1)	SHG without Magnets (i=2)	SHG with Ferrite Magnets (i=1)	SHG with Ferrite Magnets (i=2)
Rotational speed n , rpm	3450	750	3450	750
Armature phase current amplitude I_{arm} , A	369.5	676.2	375	700
Efficiency, %	90.4	79.8	92.7	84.4
Mechanical power on the generator shaft P_{mech} , kW	40	40	40	40
Shaft torque, N·m	111	510	111	510
Output electrical power P_I , kW	36.58	33.12	37.22	34.90
Armature DC copper loss $P_{arm DC}$, kW	1.90	6.37	1.29	4.51
Armature eddy-current copper loss $P_{arm AC}$, W	417	131	402	157
Stator laminated steel loss $P_{iron st}$, W	961	403	960	411
Rotor laminated steel loss $P_{iron rt}$, W	192	0	121	24
Excitation copper loss P_{ex} , W	368	1169	151	1123
Total loss P_{loss} , kW	3.84	8.10	2.93	6.22
Average losses	5.97		4.58	
Turns number in the armature slot	7.75		6.82	
Required rectifier power, kW	67.9		70.3	
Power factor	1	0.747	0.989	0.854
Line-to-line voltage amplitude V_a , V	116.0	75.3	116.0	67.4
Nonsymmetrised torque ripple, %	97.8	47.0	56	41
Symmetrised torque ripple, %	11.3	4.5	8.6	4.5
Flux density in the rotor sleeve and in the stator housing, T	0.84	1.60	0.1	1.5

Table 5: Summary of Reported Weaknesses in Experimental Studies of Homopolar Generators

Study	Focus of Experiment	Reported Weaknesses / Limitations
Avalos Zúñiga, Priede, & Bello Morales (2017)	Rotating disc with liquid metal sliding contacts	Leakage of liquid metal contacts at elevated rotation rates; voltage fluctuations; limited continuous operation (~minutes); instability in current collection; thermal and parasitic losses
Masson (2024)	Sliding and liquid metal contacts in homopolar machines	High resistive losses; maintenance burden; efficiency limitations (<98%); performance constrained by brush/contact instability under high current and speed
Patrinos (2024)	Experimental theoretical study of unipolar generator	Significant deviations between theoretical predictions and experimental outcomes; measurable losses not captured by models; rotor dynamics and high-speed operation reveal practical limitations; test durations restricted

Table 6: Validation Gaps in Homopolar Generator Studies

Study	Simulation Tool(s)	Experimental Validation	Key Omitted Effects	Impact on Accuracy
Weise, Porzig, Ziolkowski, & Brauer (2018)	FEM (COMSOL-type), coupled EM-thermal	Partial (temperature only)	Mesh dependencies, simplifications in conductor modelling	Risk of overestimating efficiency and underestimating heat build-up in rotor
Patrinos (2024)	Analytical + simulation	Limited (voltage, torque)	Contact resistance, uneven current distribution	Misrepresents saturation and efficiency under real operation
Masson (2024)	Field-emission HPG simulations	Minimal	Brush wear, sliding contact effects	Overestimates efficiency at high speeds

2.6.2 Overreliance on Simulation without Validation

The majority of HPG investigations rely heavily on computational simulations—FEM, COMSOL, OPERA 3D, MATLAB—while experimental validation remains limited. These codes typically account for field distribution and induced voltages but omit secondary effects such as brush wear, contact resistance, or armature reaction. As a result, performance predictions based purely on simulation tend to be overly optimistic (Weise, Porzig, Ziolkowski, & Brauer, 2018; Patrinos, 2024; Masson, 2024). Table 6 highlights representative examples of such overreliance.

These gaps underscore that simulation-only approaches can misrepresent practical HPG behaviour. As demonstrated by Patrinos (2024), even minor unmodeled effects such as non-uniform current distribution significantly impact efficiency and saturation characteristics, emphasising the need for systematic experimental validation.

3.0 SYNTHESIS OF INSIGHTS

3.1 Patterns and Agreements

Throughout the literature, there is a consensus that homopolar generators (HPGs) are most appropriate for low-voltage, high-current applications with compact, mechanically uncomplicated DC sources. Their commutator-free operation and direct current output render them suitable for pulsed-power applications, like welding, railguns, and plasma experiments. Performance is mostly contingent upon magnet configuration, brush style, and rotor-stator geometry.

Although there has been a great deal of simulation-based investigation, the majority of experimental data consist of short-term laboratory experiments without standardised protocols, culminating in a consensus that HPGs' full potential remains bounded by design and operational limitations. The Lorentz force model is the best theoretical description of HPG operation, with historical context supplied by Faraday's law. Competing

scalar-vector potential models add theoretical scope but with restricted experimental support.

3.2 Ongoing Debates

- **Practicality vs. Laboratory Success:** Controlled setups report high efficiency, but real-world use suffers from heating, contact wear, and current imbalance.
- **Magnet Strategy:** Permanent magnets simplify design but cap flux density; electromagnets and superconducting coils achieve higher fields but increase complexity.
- **Contact Design:** Liquid-metal brushes minimise resistance yet pose safety and stability issues; solid brushes wear rapidly under high current.
- **Model vs. Experiment:** Simplified simulations often neglect eddy currents and thermal effects, overstating efficiency.
- **Theoretical Completeness:** Debate persists over whether classical electrodynamics fully describes unipolar induction or if relativistic formulations are required.

3.3 Emerging Research Directions

- **Hybrid Excitation and Materials:** Using ferrite magnets and windings in the stator can decrease torque ripple and increase controllability.
- **Superconducting Designs:** HTS coils provide enhanced magnetic flux and efficiency but encounter cost and integration challenges.
- **Advanced Contact Systems:** Brushless HPGs and multi-contact fibre or foil brushes seek to increase durability and heavy-load stability.
- **System-Level Testing:** Researchers demand comprehensive studies incorporating thermal, vibration, and electromagnetic effects to fill laboratory and industry scales.
- **Improved Modelling:** Synchronising electromagnetic, thermal, and mechanical simulations may yield more accurate performance predictions for design optimisation.

4.0 CONCLUSION

4.1 Summary of Literature Trends

Modern HPG research focuses on enhancing efficiency, scalability, and reliability through design optimisation, hybrid magnet excitation, and high-end modelling. Materials science advances such as in rare-earth magnets, ferrites, and superconductors, have alleviated some historical limitations such as low voltage and resistive losses. FEM analysis is now central to prototyping and verification, while applications are still largely focused in pulsed-power, defense, and welding systems, with growing interest in renewables integration and transportation technologies.

4.2 Identified Gaps

- **Brush Contact Resistance:** Still constrains efficiency and life due to wear and arcing.
- **Thermal Management:** Ineffective cooling measures for extended high-current operation.
- **Material Constraints:** Relatively few studies of contemporary composites for contacts, stators, and rotors.
- **Experimental Validation:** Heavy reliance on simulation with too little long-term testing.
- **Economic Feasibility:** Very limited lifecycle or cost–benefit analyses relative to batteries or flywheels.
- **Reliability Data:** No systematic analysis of ageing, maintenance, or degradation during extended operation.

4.3 Recommended Future Research Directions

In order to bring the results of homopolar generator research to a practical technology, it is important to focus future research on three strategic areas:

1. **Design and Manufacturing Optimisation:** Integrate *design-for-manufacturing* (DFM) principles to develop modular, scalable prototypes. The target outcome is to develop a reproducible HPG design by use of standardised parts which can be fabricated by commercial companies.
2. **Experimental Validation under Realistic Conditions:** Conduct long-duration and variable-load experiments to assess *thermal behaviour, mechanical wear, and fault response*, in order to prove valid datasets between the results of the simulation and the real performance measures.
3. **System-Level Integration and Economic Feasibility:** Investigate how HPGs can complement renewable energy systems and microgrids, focusing on *rapid energy discharge and high-power buffering*. Provide comprehensive techno-economic case studies of lifecycle costs, periods of maintenances, and other energy density with other technologies such as power batteries or flywheel power.

The ultimate goal is to close the existing gap between theory and practice and make the homopolar generator, a competitive element in the overall context of sustainable high-power energy systems. ■

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Jasmier Q. Ocampo	Writing original draft preparation, literature review, review, editing, and final manuscript approval; Data collection, methodology, and formal analysis.
Great Christian C. Galing	Data collection, methodology, and data validation.
Shawn Bhryle D. Mendioro	Data collection, methodology, and data validation.
Alexander T. Montero	Conceptualisation, supervision, and data validation.
Federico Roy A. Jr.	Conceptualisation, supervision, and data validation.

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